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Manufacturing Methods and Technology

# Isothermal Roll Forging of T55 Compressor Blades



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December 1977

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The objective of this manufacturing technology program was to demonstrate feasibility to produce T55 compressor blades by isothermal roll forging within 0.010 inch of drawing tolerances. This objective was accomplished through process definition and application to blades in Ti6Al4V for proofing and in AM-350 steel for the T55 engine. Satisfactory structure and mechanical properties were achieved in AM-350 steel after isothermal rolling. Cost analyses showed good potential for progressive cost reduction with continued work over present methods of production.

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## FOREWORD

This interim report on Phase I of Contract DAAG-46-76-C-0043 on "Isothermal Roll Forging of T55 Compressor Blades" covers work performed by Solar Turbines International from May 10, 1976 to September 10, 1977. Support under subcontract was provided by the Lycoming Division of Avco Corporation.

Phase I of this contract presents the data to substantiate feasibility of the isothermal roll forging process. Phase II work has been started and will produce blades within drawing tolerances.

The controlling office for this project was the U.S. Army Aviation R&D Command with monitoring by the Army Materials and Mechanics Research Center (AMMRC). The Aviation R&D Command liaison engineer was Mr. G. Gorline. The technical supervision of this work was under Mr. Roger Gagne of AMMRC.

This project has been conducted as part of the U.S. Army Manufacturing Methods and Technology Program, which has as its objective the timely establishment of manufacturing processes, techniques, or equipment to ensure the efficient production of current and future defense programs.

This program was conducted in the Advanced Manufacturing Technology Laboratory of the Solar Research Laboratories, with Dr. A.G. Metcalfe, Associate Director of Research as Technical Director. The Principal Investigator on this program was Mr. Fred K. Rose., Research Staff Engineer.

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# 1

## INTRODUCTION

This Phase I Report presents work accomplished in the first phase of a three phase program to apply isothermal roll forging to the manufacture of compressor blades. The Avco Lycoming T55 engine compressor blade has been selected for this manufacturing demonstration with Avco Lycoming providing engineering support under subcontract. The work reported was performed in the period May 1976 through September 1977.

The first phase of this program, reported here, will provide a demonstration of the isothermal roll forging process by production of proof blades to establish process reproducibility and process costs. The blades were not expected to be precisely within the envelope for the T55 blades but the maximum deviation was not to exceed 0.010 inch. The second phase of the program will be the establishment of a production process with hard tooling and evaluation of production type runs by non-engine tests. The goal of this phase will be an acceptable blade fabrication process capable of producing engine-quality blades.

The isothermal roll forging process is based on the isothermal metal working processes applied first to diffusion bonding and subsequently expanded to perform a wider range of metal shaping. The diffusion bonding process has been applied to aircraft and engine components with the most notable application being to the turbine seals on the General Electric CF6 engine. Here, two 12-foot long strips of Hastelloy X are roll forge welded together, without fusion, to produce a T-section with low stress concentration fillets. The method is based on use of refractory metal roll electrodes that apply the forging pressure and heating current to the component. In the roll forging process applied to compressor blades, molybdenum alloy roll forging dies replace the rolls. The isothermal roll forging process mechanically resembles the cold, knuckle rolling process that is widely used for production of compressor blades in alloys that can be cold worked.

The isothermal roll forging process was originally conceived for materials that could not be cold rolled, especially for titanium alloys. Considerable experience was gained in all processing aspects of titanium in work at Solar, and selection of the Avco T55 engine was made at the time when the first two stages of blades were required in Ti6Al4V alloy. During the early stages of the program development, a change was made from Ti6Al4V to AM-350 for two primary reasons: cost reduction; and improved erosion resistance. Application of isothermal roll forging to the AM-350 blades became more challenging technically because of the higher forging temperatures required, as well as more challenging economically because the cost target to be

equalled had been significantly reduced. The influence of this factor on the program is pointed out in this report. On one hand, the stimulation of these technical and economic challenges led to a more sophisticated isothermal roll forging process than those considered initially. On the other hand, this additional challenge required a time extension from 12 to 16 months and led to some shift of effort between tasks. However, the more sophisticated process is known to be more effective than previous processes with titanium alloys and promises to have significant advantages once it is applied to titanium.

The most critical areas on a compressor (or fan) blade are at the transition radii from platform to airfoil. Defects in this region such as forging laps or undercuts from handwork are most frequently associated with blade failures. One of the objectives of the isothermal roll forging method was to produce forgings that would avoid laps and not require hand work; it is believed that the process described meets these criteria. Another objective was to forge the leading and trailing edges with precision of contour retained up to a thin flash so that amount of edge finishing required would be minimized. This reduces the cost of handwork and the increased scrap associated with departures from aerodynamic contours.

This report presents technical details of the process selected as well as preliminary cost data and an examination of the steps under way to apply the process to engine blade production. It is concluded that the initial promise of the isothermal roll forging method continues to be good and work in Phase II is expected to reach the goals planned at the start of the program.

# 2

# FABRICATION OF COMPRESSOR BLADES

Current methods used to fabricate compressor blades are reviewed to provide a background for the introduction of the isothermal roll forging process. The review is designed to help identify the principal sources of cost so that the work can be planned to realize maximum cost savings. Major emphasis is placed on the potential cost savings because the large number of compressor blades required per engine makes these components a major contributor to jet engine costs.

## 2.1 CURRENT METHODS OF FABRICATION

The principal methods for fabrication of compressor blades are:

- Machining from solid
- Casting
- Hot die forging
- Cold roll forging.

Machining from solid stock is often used for small quantities of blades, but has had to be adopted to an increasing extent in recent years for production of blades in the more heavily alloyed materials. The latter include AM-350 steel and Inconel 718 that are difficult to forge to high performance blades. However, not only is machining expensive but is needlessly wasteful of both strategic materials and energy. Both of the latter experienced step-function types of cost increases fall in the year or two following the Energy Crisis of late 1973.

Casting may be more economical in material consumption and has been used to produce compressor blades but the individually cast blades do not offer an economic advantage for high performance engines.

Hot forging cannot form the precision shapes required for high performance engines and must always be followed by a certain amount of machining on all surfaces. Although the amount of metal to be removed is very much less than in machining from solid, the operations are expensive because they are precision rather than roughing cuts, and involve much hand labor to blend the machining cuts together. It is noteworthy that two of the three critical problems identified by Avco in inspection of blades, viz.,

- Transverse grooving
- Root radii control
- Transition at root

are the result of hand blending operations in the manufacture of the blades.

The cold roll forging process is the most widely used method for production of steel and low alloy blades. It provides high quality, precision surfaces over much of the airfoil. Its major disadvantage is the large number of operations required. Up to 11 roll forging passes may be used, followed in each case by lubricant removal, annealing and relubrication. The number of roll forging passes is dependent on the rate of work hardening, thickness of leading edge (LE) and trailing edge (TE) and other factors, but will always be high. In addition, many other operations are required between passes including trimming and inspection, plus additional operations for root upsetting, twisting and broaching. Hand finishing to remove flash and blending of airfoil to platform are also significant contributors to cost both by increasing the in-process inspection and by reducing the yield of acceptable blades. Some of the principal operations in blade manufacture by this method are shown in Figure 1 for a cold-rolled compressor blade in 17-4PH steel used in a Solar turbine. In the case of the AM-350 alloy, an additional requirement is that the metal temperature be kept at 350°F or above to prevent transformation to martensite.

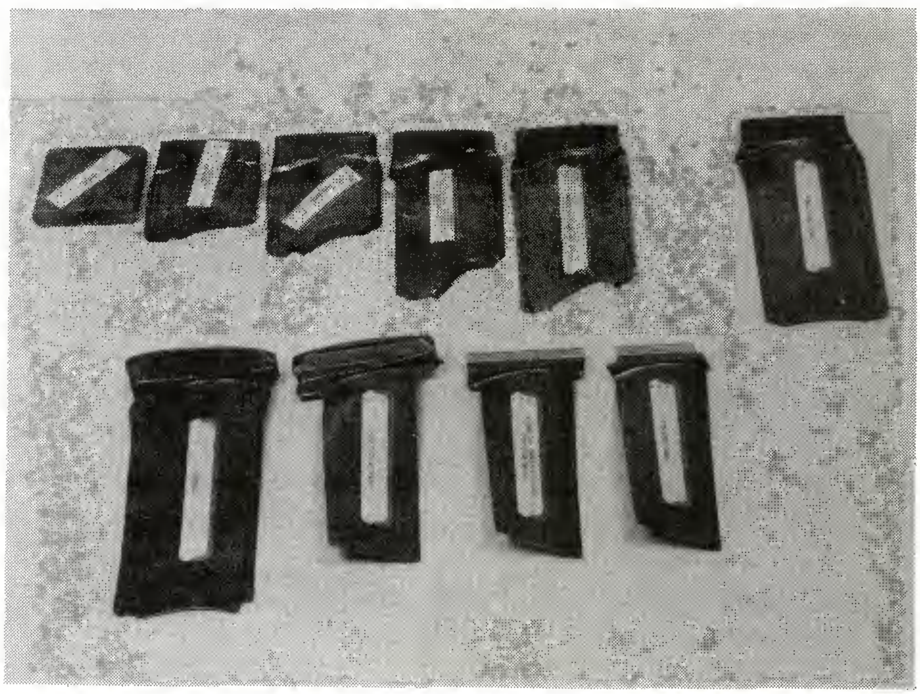


Figure 1. Some Stages in Cold Roll-Forging of Compressor Blade in 17-4PH Steel (#76-2679)

## 2.2 THE ISOTHERMAL ROLL FORGING METHOD

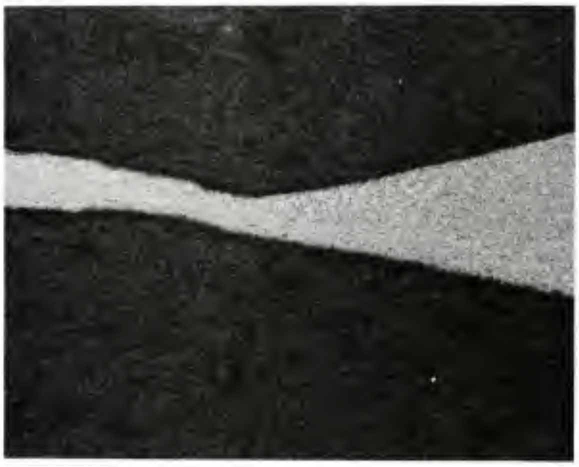
The isothermal rolling and roll forging methods are based on use of refractory metal rolls or dies. The latter are heated together with the workpiece by a flow of controlled electric current. The control may be provided by feedback from a temperature sensor, although the process is inherently stable because there is a certain degree of self control. The latter arises because the size of the footprint between roll or die and workpiece seeks a constant value. When operating under constant current conditions, any change of gage causes a corresponding change in current density (temperature) and pressure that tend to maintain constant gage.

An important finding early in the development of the isothermal processes was that force feed could be used to prevent roll slippage at large reductions, and that this would increase the lateral spreading of the metal. One of the earliest applications of this concept was important to the current program. Round barstock of materials, such as 17-4PH steel, Ti6Al4V alloy and Rene´ 95 superalloy were rolled from 0.375 inch diameter to an airfoil with 1.3 inch chord in a single pass. Figure 2 shows this operation in progress. The force feed is 6000 pounds with approximately 200 pounds of tension to maintain straightness.

Important features of the airfoil rolling process were that excellent surface finishes were obtained (typically 16-32 rms) and that the contour was preserved up to the flash. Figure 3 shows a section of an airfoil to confirm the thin flash that can be produced. In views (A) and (B) the sections have been produced from 0.375 inch diameter bar in one pass. Very thin LE and TE contours can be produced for the higher performance compressors required in advanced gas turbine engines.

Figure 4 shows schematically one approach to the application of the isothermal roll forging technology to compressor blade manufacture.

Figure 2. Single Pass Isothermal Rolling of 0.375 Inch Bar to a Contoured Airfoil With 1.3 Inch Chord. (Note bar emerging from force feeder guide on right) (#76-0961)



A. Leading Edge "As-Rolled"
0.0024 Inch Flash
Magnification: 75X

B. "As-Rolled" Airfoil
Magnification: 3.5X

C. After Sweco Finishing
Magnification: 3.5X

D. "As-Rolled" Surface
Magnification: 500X

Figure 3. Isothermal Rolled Ti6Al4V Bar (Single Pass) (#74-2000)

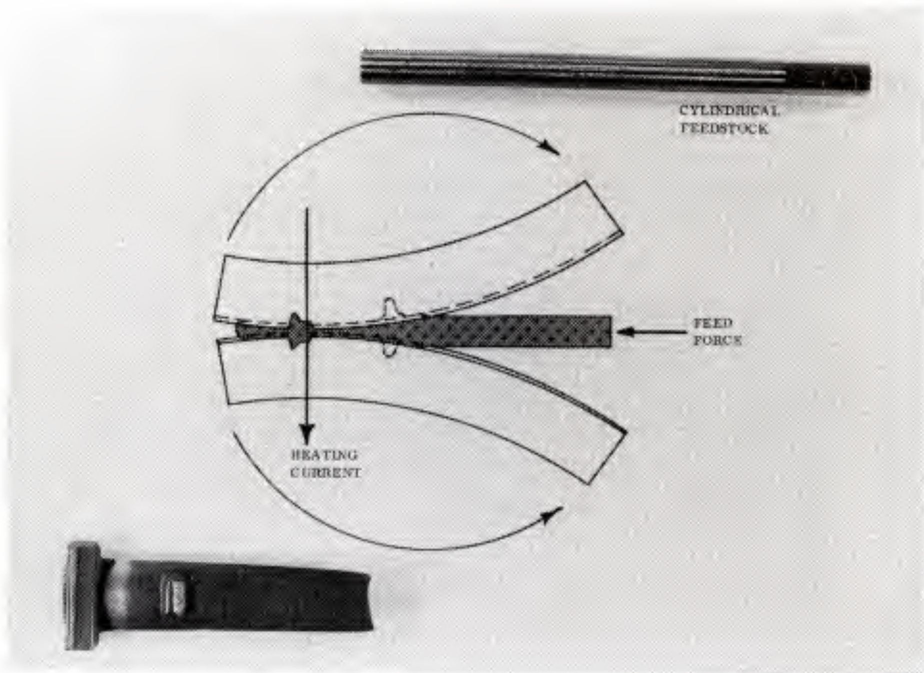



Figure 4. Isothermal Roll-Forging From 0.375 Inch Ti6Al4V to Simulated Mid-Span Shrouded Blade in One Pass

## 2.3 COST FACTORS

Preliminary analyses were made prior to the start of this program to identify the sources of cost savings and to make preliminary estimates of potential costs.

The major sources of cost savings were identified as:

1. Reduction in the number of operations.
2. Reduction in the amount of hand work required.
3. Reduction in the number of inspection steps as a result of #1 and #2.
4. Reduction in scrap as a result of #1 and #2.
5. Improvement in metal recovery.

### 2.3.1 Reduction in Number of Operations

Several prior studies have shown that manufacture of a net shape in a single pass leads to economy of operation. Some of the sources of cost reduction include:

1. Elimination of inter-operation handling.
2. Elimination of inter-operation inspection.
3. Reduction in clean-up required after each operation including: flash removal; lubricant removal; descaling; etc.
4. Reduction in preparation for subsequent operation including: stress relief annealing and/or heat treatment; lubricant application; etc.
5. Manufacture and maintenance of multiple tool sets.
6. Multiple tool set-ups and proofing.
7. Increased scrap due to stack-up of tolerances from successive operations.

### 2.3.2 Reduction in the Amount of Hand Work

As pointed out earlier, the large reductions required to achieve the thin LE's and TE's needed in compressor blades are difficult to achieve in a cold rolling process. Stone (Trans. ASME, Jour. of Basic Eng., December 1959 No. 681-686) gives the minimum gage, $t_{min}$, achievable with steel rolls of diameter D and elastic modulus E when rolling a material with a constrained yield stress $S_o$, as

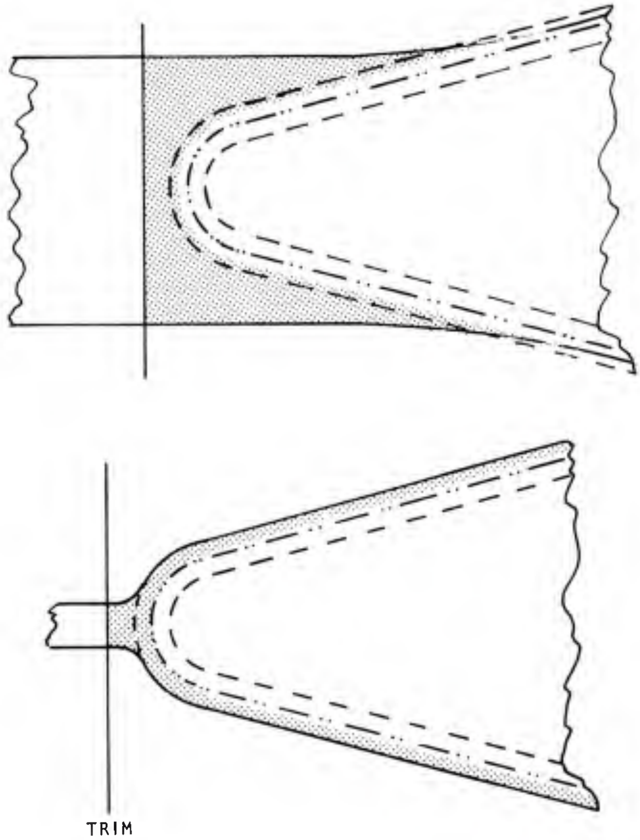
$$t_{min} = 3.58\mu \frac{DS_o}{E}$$

where $\mu$ is the coefficient of friction. This limiting gage is increased by work hardening (increased $S_o$) because this raises the roll pressure and hence the elastic roll flattening. For example, if $S_o$ = 100,000 psi after work hardening, $\mu$ = 0.07, D = 12 inch, then, $t_{min}$ = 0.010 inch.

A blade with a TE thickness of 0.010 inch would not thin below this amount. Elastic flattening of the roll (die) would decrease away from the TE leading to a condition as depicted in Figure 5. Gradual departure from the tolerance band (dashed) would occur until the nominal size was met back from the TE. Hand finishing to restore the tolerances to the band will be required after trimming of flash (assumed to be 0.010 inch in this example).

Hand finishing to this extent is an expensive operation.

As shown earlier, the isothermal roll forging operation can generate flash of 0.002 inch thickness. Now the amount of hand finishing is greatly reduced with fewer problems in holding contours. In addition, as shown in Figure 3, preliminary work indicates that automatic edge finishing operations may be possible with major reduction in labor and reduced scrap caused by lapses on the part of the operator.




A. Operations in Cold Rolling

(1) Roll to within tolerance band leaving a 10-mil flash.

(2) Trim flash.

(3) Hand finish to outside limit of tolerance band by belt.

B. Operations in Isothermal Roll Forging

(1) Roll to outside of band leaving a 2-mil flash.

(2) Trim flash.

(3) Barrel finish to move airfoil within band and finish edge. Shaded area shows metal removed.

Figure 5. Comparison of Airfoil Edge Finishing Operations

There is another major advantage in elimination of hand operations. General Richard E. Merkling, Director of Aerospace Safety for the U.S. Air Force in a keynote address at the Third Annual Propulsion Materials Roadmap Review in Dayton, June 6, 1977, noted that undercuts from hand working TF34 fan blades had been responsible for at least one fatal crash. Engines and engine materials were the largest single cause of serious accidents. Figure 6, from his talk, shows that compressor blades and fan blades are a major source of accidents. Reduction of hand work may reduce costs and, at the same time, increase reliability.

### 2.3.3 Reduction in Number of Inspection Steps

As pointed out earlier, a major advantage of reducing the number of operations is that the attendant inspections are decreased. Inspection always presents a problem. With too little inspection, discrepant products may be carried forward to an excessive degree; whereas with too much inspection, the costs of the work becomes excessive and parts remain for

## ENGINE MATERIEL PROBLEMS

- COMBUSTION CASES
- COMPRESSOR BLADES/VANES
- FAN BLADES
- MAIN BEARINGS
- ROTATING PARTS LCF
  - SPACERS
  - HEATSHIELDS
  - DISKS
- TURBINE BLADES/VANES
- QUALITY CONTROL

Figure 6. Principal Causes of Engine-Sources of Aircraft Accidents (see text for reference)

longer periods in the shop. On the other hand, bench type inspection methods, such as guillotine gages and radii measurement tools may be indispensible to efficient conduct of hand finishing work.

### 2.3.4 Reduction in Scrap

Low scrap production is achieved by tight control of each operation so that the individual probabilities are reduced. But, low scrap production can also result from reduction in the number of operations. It is expected that this result will be experienced with isothermal roll forging where the number of operations can be significantly reduced compared with competing methods.

### 2.3.5 Improvement in Metal Recovery

In a typical case, the cold rolled compressor blade shown in Figure 1 weighs 177 grams before broaching and is produced from the 367 gram blank shown in the first position. This is a metal recovery rate of 48 percent at this stage. Much lower metal recoveries are found in hot forged blades. Some improvement in metal recovery is expected in the isothermal roll forge process over existing methods.

# 3

## WORK ACCOMPLISHED

The objectives of the first phase are: (1) to demonstrate the capability of isothermal roll forging by manufacture of the second stage compressor blade of the Lycoming T55-L-11A engine to within 0.010 inch of the drawing dimensions; and (2) to gain experience with tooling and processing that will enable prototype blade production within drawing tolerances during Phase II. As pointed out earlier, a change in blade material from Ti6Al4V to AM-350 was made between the time of the proposal submission and the start of work. Although Solar had considerable experience in the isothermal rolling and roll forging of titanium and no experience with AM-350 steel, it was believed that the same tooling and roll forging methods would be applicable based on limited work on a similar steel, 17-4PH. Work began in May 1976. However, the AM-350 steel was more difficult to roll forge and the work in Phase I was not completed until September 1977. This report presents the results of the work in Phase I that has led to identification of the process and demonstration of this isothermal roll forging process.

The original plan identified nine tasks that needed to be completed to lead to the successful demonstration. In addition, the original work statement required that Solar initiate steps to ensure availability of a production source on completion of the first phase with demonstration of a reproducible, low cost production method. Although these steps were planned to be concurrent with the two-phase program, and not start until completion of Phase I, some work has been accomplished along these lines.

The nine tasks are:

- Task 1 - Process Definition
- Task 2 - Process Selection
- Task 3 - Tooling and Materials
- Task 4 - Preform
- Task 5 - Properties of Isothermal Roll Forged AM-350
- Task 6 - Rough Roll Forging
- Task 7 - Finish Roll Forging
- Task 8 - Final Operations
- Task 9 - Evaluation

It must be appreciated that even in a Manufacturing Technology program, the findings in an earlier task may detail the plans for a subsequent task. However, the tasks continue to represent the major steps in which the process and processing parameters must be defined for a production process. The report presents the results based on this format.

## 3.1 TASK 1 - PROCESS DEFINITION

This first task involved dividing the isothermal roll forge process into its basic elements, defining the various alternatives within each element, discussing the merits of each alternative, and finally selecting the process. The definition and selection task was supported by work at each decision point.

Also included in Task 1 is the overall planning for Phase I. This plan which is presented in Figure 7 as a flow chart shows three parallel activities involving the workpiece, processing and tooling. These come together at midphase for the establishment of forging parameters and final operations, concluding with process evaluation and reporting.

Task 1 primarily is concerned with the processing portion of the flow chart (Fig. 7), which is shown enlarged in Figure 8. This figure shows three tiers of processing involving: (1) basic approach; (2) dimensional control; and (3) surface and temperature control. Decisions were to be made at each step in the progress from the top to the bottom of the chart. However as discussed below under Task 2, the decision on basic approach was changed following experiments on root platform control and identification of a superior method to those outlined in Figure 8.

The basic approach to blade manufacture required the selection of either continuous or noncontinuous roll forging. Factors in this choice included:

- Continuous Roll Forging - Single pass roll forging of blades in a continuous manner from simple feedstock would probably provide the maximum cost reduction. To illustrate the concept, a matched pair of rolls of approximately 12-inch diameter with blade contours machined into the periphery would produce ten 3-inch blades per revolution. By means of axial and torsional forces applied to the feedstock, airfoil rolling, root upsetting and blade twisting would be combined into a single operation.

- Discontinuous Roll Forging - Roll forging of blades on an individual basis. The cold, roll forge process currently used for much of the current blade production is a discontinuous process.

The discontinuous method was selected late in Phase I when the advantage of the die injection method for root formation was fully recognized. The injection method avoids laps in the critical root-to-airfoil transition zone by first heating and squeezing the feedstock with the dies stationary at the

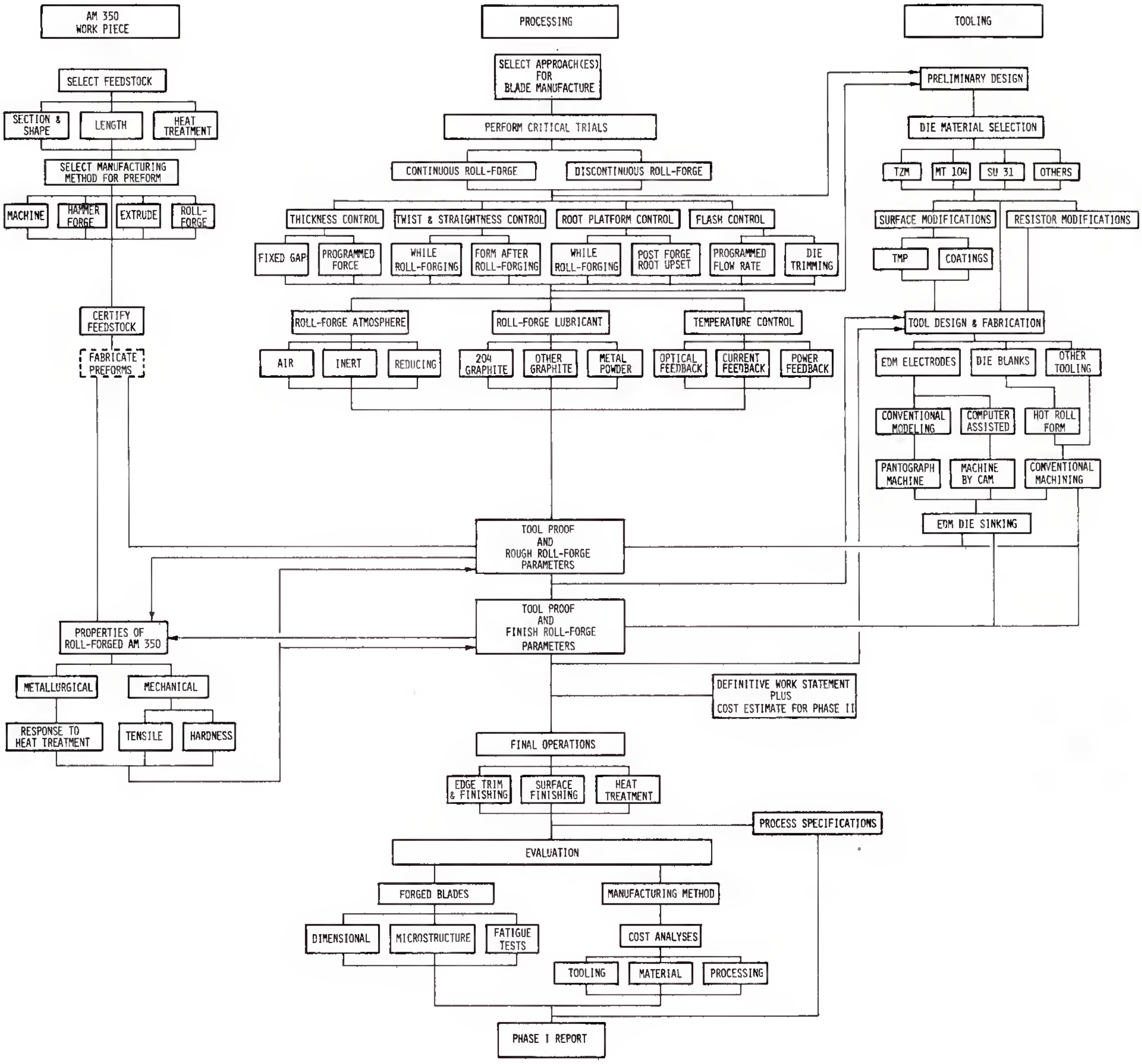



Figure 7. Phase I Flow Chart

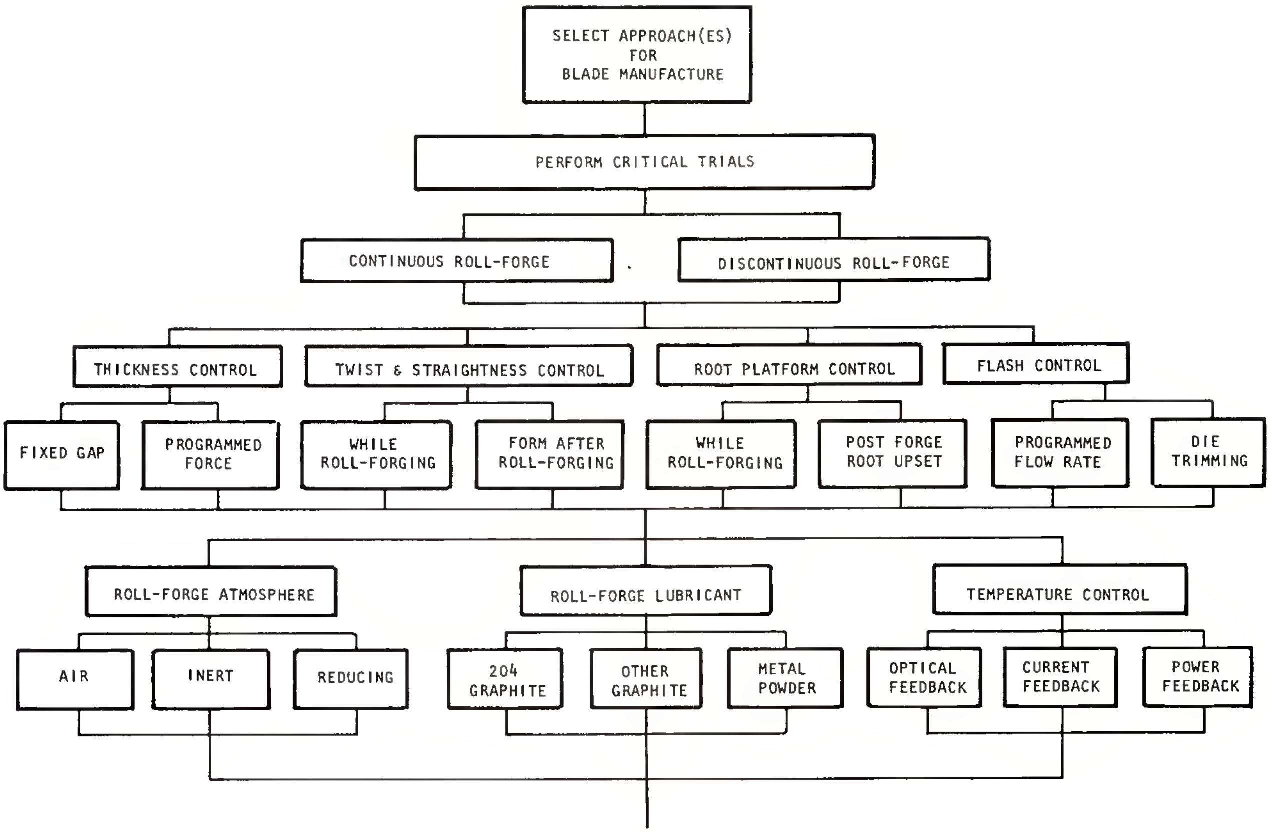



Figure 8. Process Flow Chart

root platform position, followed by injection of feedstock from the root end of the dies. It was learned that injection from the tip end of the dies must be avoided as it caused forging laps. The continuous roll forge approach is incompatible with the root injection method because: (1) airfoil rolling must proceed from root to tip; and (2) it would be impractical to apply the high force needed for root injection through a previously forged blade.

### 3.1.1 Thickness Control

Figures 7 and 8 indicate two methods of thickness control by fixed gap or programmed force.

- Fixed Gap - This method relies on mechanical stops to fix the position of the moving platten of the roll forging machine relative to the stationary platten.

- Programmed Force - Thickness control can be achieved through control of force or position. Force control has been used successfully for isothermal shape rolling of beams of uniform sections where steady state conditions were maintained. Because of

rapidly changing sections, damaging contact between dies could not reliably be avoided with force control for blade roll forging. Position control would maintain constant die gap as measured by a feedback transducer.

Fixed gap was selected as superior to programmed force for thickness control of blades in Phase I because it was essential that die-to-die contact be prevented. Four steel bars, one at each column of the four posted forging machine, were used to fix the minimum distance between the plattens which support the bearing, shafts and die assemblies. Elastic deflection of these stop bars at 40,000 pounds squeeze would tend to open the die gap as much as 0.010 inch as distribution of the load to the workpiece increased. Subsequently, analysis suggested that this could account in part for the tendency to overthickness at the tip of the blades forged in the later stages of Phase I.

### 3.1.2 Twist and Straightness Control

Figures 7 and 8 illustrate two methods for twist and straightness control, as discussed below.

- <u>While Roll Forging</u> - The hot blade, as it emerges from the rolling dies may be bent, stretched or twisted. If unassisted, the forging tends to take the curvature of the lower die simply due to its weight. Ideally the application of axial tension and torsion will produce a straight blade with the proper twist.

- <u>Form After Roll Forging</u> - Twist and straightness are currently achieved in the case of cold, roll forged steel blades by coining in steel dies. Hot isothermal pressing in refractory dies may be advantageous with some blade material to achieve twist and straightness control.

### 3.1.3 Root Platform Control

Figures 7 and 8 show two methods for root platform control. Root platform control includes the forming of the transition radii, platform faces and a root enlargement with adequate envelope for subsequent root broaching. The object is to forge the transition radii and the platform in a finished condition so that additional machining is not required to meet drawing tolerances. The approaches to platform control are considered below:

- <u>While Roll Forging</u> - This represents a new approach to root platform control that is possible with the isothermal roll forge process for two reasons: (1) axial forces are applied to the feedstock to control metal flow between the roll forge dies; and (2) only the metal currently between the dies is heated thus localizing the desired metal flow to that region. Platform control

while roll forging is achieved by initially forming the root by the injection method while the dies are stationary immediately followed by root-to-tip roll forging of the airfoil.

- Post Forge Root Upset - This approach represents the current state-of-the-art of the blade roll forging industry. The blade airfoil is first roll forged, then in a separate operation, the airfoil is clamped in a die and the free end of the root is upset by application of an impulse force. As the root upsets, metal conforms the internal surfaces of the dies thus forming the transition radii, platform surfaces and root enlargement. This method had been studied previously for isothermal roll forged blades and appeared to be a candidate.

### 3.1.4 Flash Control

The last item in the second tier of Figure 8 relates to flash control. In roll forging, metal in excess of that needed to fill the die contours escapes axially in front of the advancing dies and laterally over the flashlands at the edges of the airfoil. Obviously, complete die fill is essential. However, to minimize the costs associated with hand finishing of blade edges, and to maximize die life, it is important to avoid excessive overfill and to minimize the thickness and volume of lateral flash formation. Two methods for flash control were examined.

- Programmed Flow Rate - In isothermal roll forging lateral metal flow is strongly influenced by axial forces applied to the feedstock at the inlet side of the dies. As the compressive feed force is increased the metal being forged widens more and elongates less. Through this mechanism a wide range of control is possible, ranging from several hundred percent elongation at low force to zero elongation at high force where all metal flow is lateral. It follows from this analysis that at an ideal intermediate force level, total die fill could be achieved with zero flash formation.

- Die Trimming - This method would use conventional die trimming to remove flash. Should reliance be made on this more conservative method it would remain important to control flash formation while roll forging to minimize flash thickness for the reasons mentioned above.

### 3.1.5 Roll Forge Atmosphere

The third tier of processing steps in shown in Figure 8 to include three major portions of the process. The first of these is roll forge atmosphere.

Isothermal rolling with refractory metal dies is typically performed in air. Figure 2 shows titanium alloy vanestock being rolled with a molybdenum alloy roll set at 1725°F without use of protective atmosphere. Oxidation is

negligible because the material is not heated to incandescence until it is between the rolls. During the few seconds at temperature, air is largely excluded from the heated surfaces by the contacting rolls. However, when rolling stainless steels or superalloys, temperatures in excess of 1900°F are required and oxidation does become a problem. It is expected that isothermal roll forging of blades in AM-350 will be marginal in air. It may be possible but die life will probably be shortened, lubricants may be oxidized and friction control will be uncertain.

### 3.1.6 Roll Forge Lubricant

Figure 8 shows that three types of roll-forge lubricant were under consideration. This lubricant must perform the usual function of enhancing metal flow over die surfaces, but additionally it must be a low resistance conductor of electric current and it must be nonreactive with the workpiece and the dies at the forging temperature. Graphite base compounds and some metal powder or flake are the principal candidates. A dry graphite lubricant applied as an aerosol (Sprayon 204) has been used successfully for isothermal roll forging blades in Ti6Al4V and IMI-685 titanium alloys, and for isothermal rolling of T and L sections in titanium, steels and superalloys. Water suspended graphites are more difficult to apply uniformly and tend to build up on the die surfaces. Slurries of very fine refractory metal powders are effective in preventing adhesion of the workpiece to the dies but more work is needed to improve application techniques.

### 3.1.7 Temperature Control

The last control function shown in the third tier of Figure 8 is that of temperature. While isothermal rolling elongated parts of constant sections, steady state conditions are rapidly attained and workpiece temperature becomes directly related to heating current. Indirect temperature control through direct control of current depends on constant voltage drop between the electrode rolls (dies) and the workpiece (or a reliably predictable voltage if variable with time), steady state or predictable thermal losses to the various heat sinks, and a constant rolling speed. These conditions are difficult to achieve when roll forging short parts and/or parts with rapidly changing section. It was concluded that reliance on current control would be inadequate for blade forging.

Another approach to temperature control is through control of electrical power dissipated in the dies and workpiece. This approach compensates for voltage fluctuations in the vicinity of the workpiece and moves one step closer to reliable temperature control, leaving only heat sink effects unaccounted for.

The direct approach to temperature is through thermal energy radiation control. Radiation from a target area on the workpiece is collected by a suitable lens system onto a infrared radiation detector that provides an

electrical feedback signal proportional to workpiece temperature. This approach has been highly successful on applications such as a isothermal rolling of T-sections or turbine vanestock where good optical access to the heated target is available.

It was planned to evaluate all three methods for temperature control for blade roll forging. It was recognized that the best method for control of airfoil rolling might not be the same at that used for the root forging.

## 3.2 TASK 2 - PROCESS SPECIFICATION

At the beginning of Phase I several approaches to blade manufacture had been identified. These approaches were based on different combinations of operations such as preform formation, rough and finish roll forging, and finishing operations as depicted by the flow chart shown in Figure 9. The choices to be determined ranged from an approach including as few as one to many as five separate forging operations. The general approach was to upset the root after the blade airfoil was roll forged in conformity with general practice in the cold roll forging industry. After six months of forging trials and process selection the approaches to blade manufacture were revised as shown in Figure 10. The principal change in approach was to reverse the sequence and make root upsetting the first operation. This change had great significance to the program for two reasons: (1) it eliminated forging laps in the critical root to airfoil transition; and (2) it changed the basic approach from continuous to discontinuous roll forging.

The manufacturing approach selected as best for the T55 second stage blade in AM-350 is shown by the heavy path in Figure 10. The sequence of operations along this preferred path are as follows: lengths of rectangular barstock are cold rolled to provide contours on opposite faces of the bar that conform to the initial contact point of the isothermal roll forge dies. The cold rolled feedstock is then converted into preforms by cutting to short lengths, heat treating to 160 ksi yield strength, followed by a cleaning operation consisting of degreasing and sand blasting or tumbling. Preform preparation is discussed in more detail in Section 3.4.

The first forging operation forms the root by the root injection method. In this method the preform is upset within the closed and stationary roll forge dies. Then the airfoil is rough roll forged by rotating the dies from root to tip leaving about 0.020 inch of thickness for the finishing pass. During the rough forge operation axial forces of different magnitude and direction are applied sequentially to the feedstock. First a compressive force is applied to the root end causing the short zone of hot metal which had been heated between the dies to upset and to fill the root pockets. Second, the root force is removed and a compressive force is applied to the tip end of the blade as die rotation is started. This force does two things: (1) it feeds the stock into the dies and makes thickness reduction exceeding 90 percent possible with smooth dies; and (2) it promotes lateral spreading of

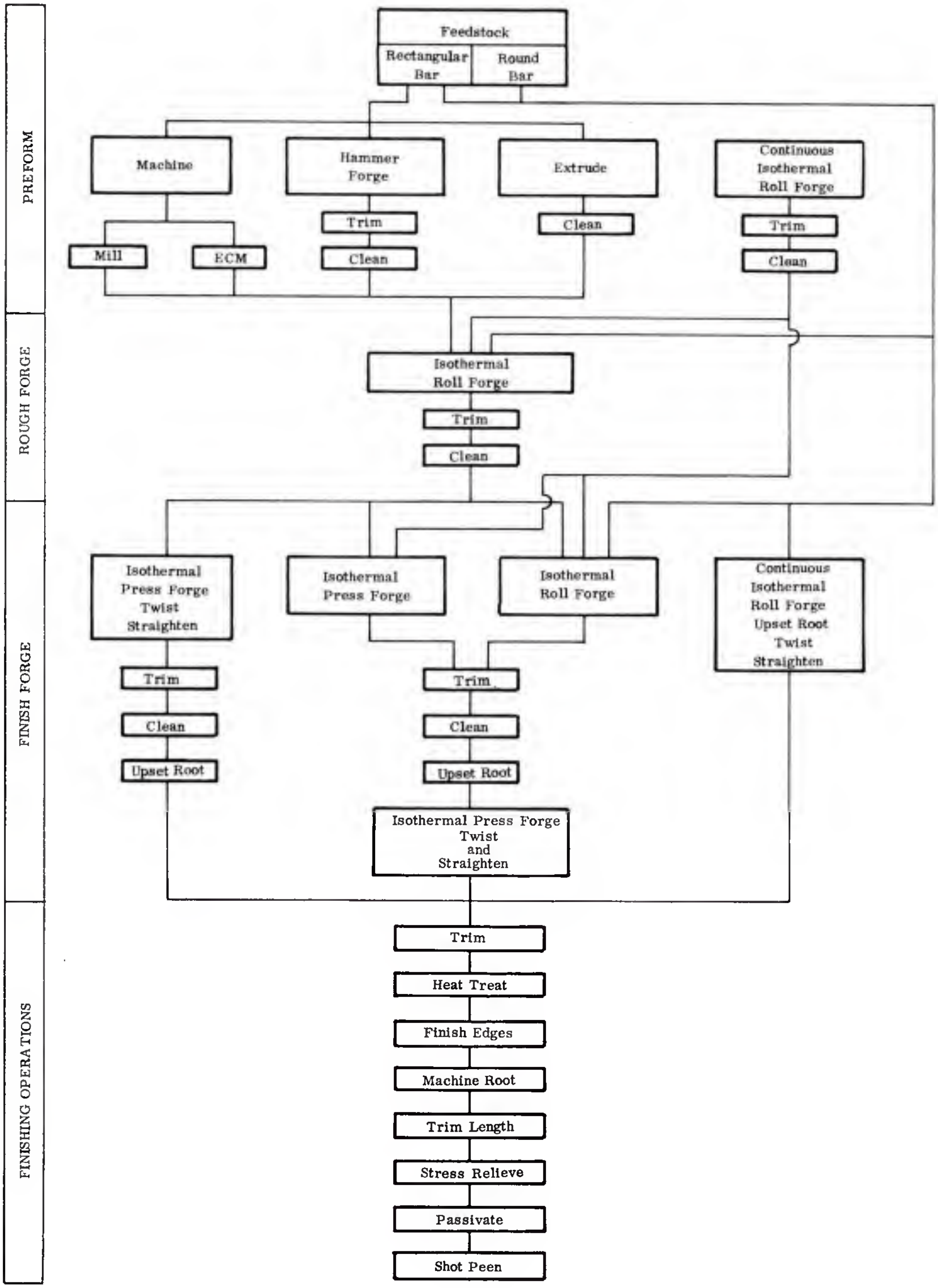



Figure 9. Approaches to Blade Manufacture

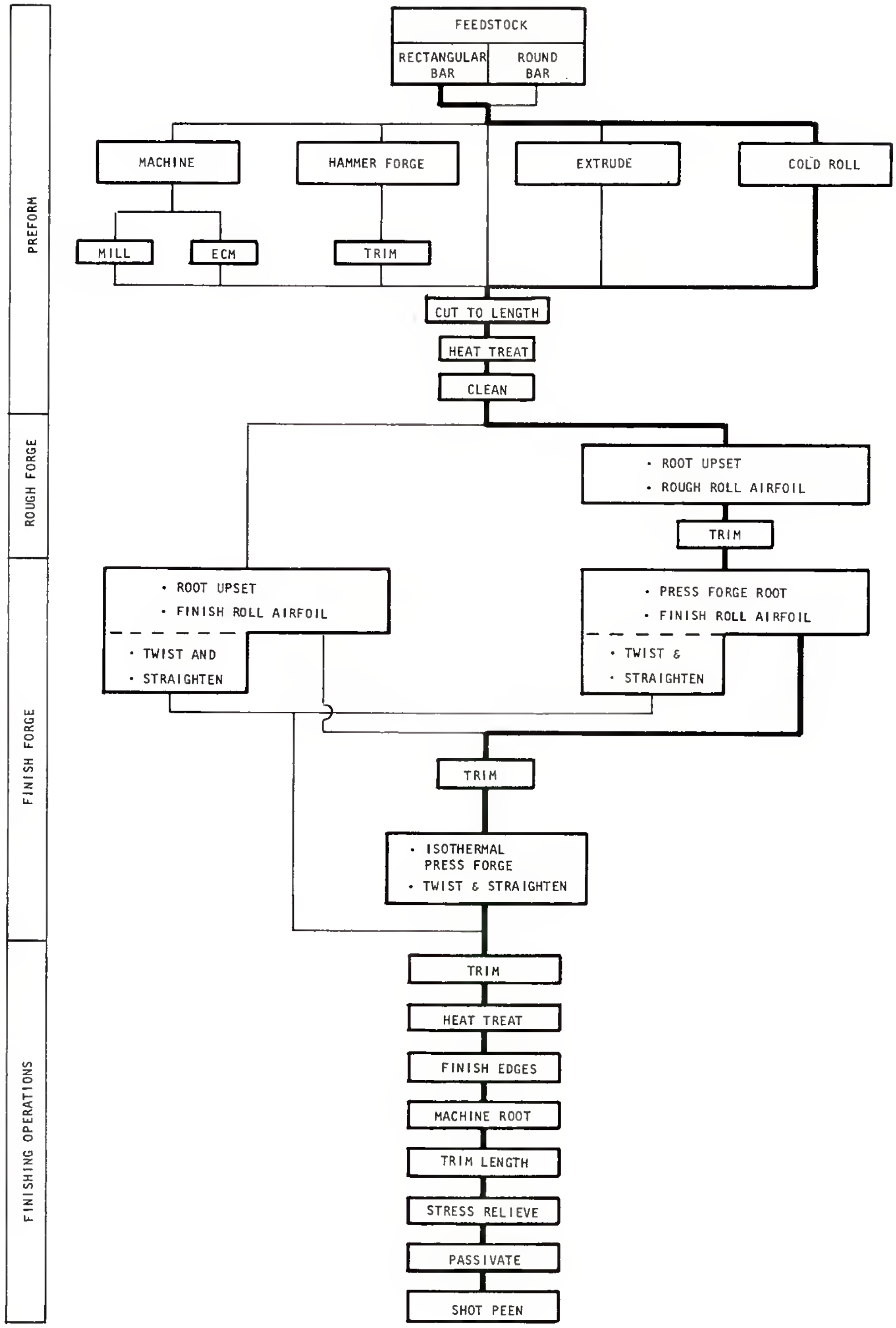



Figure 10. Selected Approach to Blade Manufacture

the metal which is needed to fill the thin leading and trailing edges of the airfoil. Concurrently a tensile force is applied to the root end to straighten the blade as it emerges root first from the rotating dies.

After flash trim, the die gap is adjusted to close at the finishing thickness and the rough forging is cleaned, lubricated and finish forged first by press forging the root with stationary roll forge dies followed by finish roll forging of the airfoil. No axial force is used during the final root squeeze. However, when the airfoil is finish roll forged a small tensile force is applied to maintain straightness and the tip end of the blade is guided to prevent chordwise shift as the blade is rolled. The airfoil then is trimmed. Twist, straightness and alignment of the stacking axis relative to the root platform is achieved by means of a hot isothermal coining operation. Conventional finishing operations then are used to complete the blade.

With additional work in Phase II, it may be possible to refine the process further by elimination of the rough forging operation and combining the twist and straightness control with the finish forging operation. This possibility for further process refinement in Phase II is based on successful single pass roll forging of titanium alloy blades during the tool proofing of Phase I.

## 3.3 TASK 3 - TOOLING AND TOOL MATERIAL

This section discusses the design, manufacture and proofing of tooling used in Phase I.

### 3.3.1 Design

The design of conventional roll forge dies primarily involves such factors as dimensions, strength and cost. Additional factors must be considered in the design of dies for the isothermal roll forge process because the dies also must function as electrodes. The approach taken in Phase I was first to select a die facing material that is an electrical conductor with: (1) high strength at the blade forging temperature; (2) good resistance to deformation and fracture when repeatedly cycled to the forging temperature; (3) reasonably machinable; and (4) available commercially at reasonable cost. Arc cast TZM molybdenum alloy cross rolled to plate best meets these criteria. Second the die facing was matched thermally to the blade being forged so that the current required to heat the blade preform to the forging temperature also would be adequate to heat the die facings to approximately the same temperature. Matching of the blade forging dies largely involved minimizing the mass of the facing and creating a barrier to heat flow into the supporting members.

The initial design of the die block is shown in Figure 11. This design provided for ten such blocks to be clustered about a pair of steel adaptor rings which attach to each shaft of the roll forging machine. The molybdenum facings were sized to the T55 second stage blade. The blade root determined the minimum thickness and width. A barrier to retard heat flow into the steel support block from the TZM facing was created by a braze joint to the steel. Forging trials showed the thermal matching to be good, however the steel/molybdenum interface temperature was found to be excessive and the large thermal expansivity difference between the two materials caused shear failure in the brazement. As a result of these findings the design was modified as shown in Figure 12. The molybdenum/steel interface temperature was reduced by placing a 0.5 inch thick layer of unalloyed molybdenum between the TZM alloy facing and the steel. Good thermal matching was retained because the additional interface tended to compensate for the additional mass. To relieve the thermal expansion problem the facings were located by means of pins and cruciform keys and were fastened in place with tantalum alloy tie rods extending through the steel block.

### 3.3.2 Tool Manufacture

The manufacturing plan for the roll forging dies was based on the use of locating pins on the side faces of the die blocks and precise die block thickness to control the position of the die contact radius and contours of the dies. Eleven auxiliary tools, all dependent on the pin locators, were fabricated for use during the numerous operations required for die manufacture. The manufacturing plan also was based on the use of electric discharge machining (EDM) for sinking the blade contours into the periphery of the roll forge dies.

The flow chart shown in Figure 13 shows the sequence of operations that were used in fabrication of the roll forge dies and where each of the auxiliary tools were used in the process. In addition to building the auxiliary tools there were three lines of activity in the die fabrication work. The first line was the modeling of the T55 blade airfoil and root pockets into the periphery of a cylinder. The second line of activity was fabrication of the die block and die facing. The third tooling activity was fabrication of the special rings needed to adapt the dies to the roll forging machine.

Modeling work was done at four times actual size using precision templates and layouts from Lycoming drawings. Master profile drawings at 20 times actual size of the T55-L-11A stage 2-blade, provided by Lycoming, were used to prepare airfoil station templates at four times size on 0.050-inch thick aluminum sheet. The maximum model size was determined by the maximum tracing area of the pantograph milling machine which was subsequently used for 1X replication of the EDM electrodes. Figures 14 and 15 show the model frames with station templates installed. The die contact radius and angular and radial position of the templates were controlled relative to the tooling balls on the lower surface of the models. Using longitudinal templates the model maker fill the models with plaster and finished the upper surface to

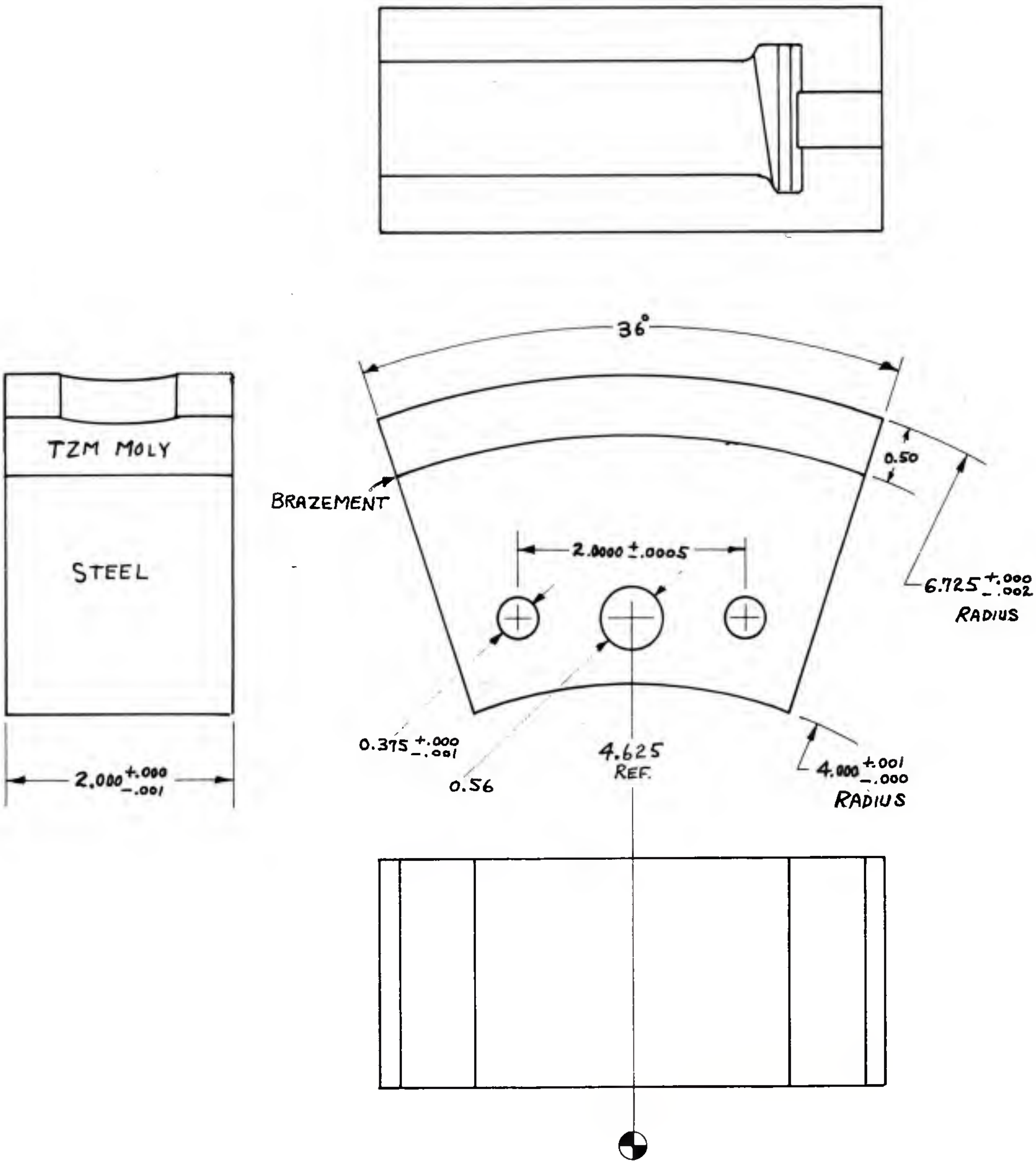



Figure 11. Die Design for Isothermal Roll Forging of T55 2nd Stage Blade

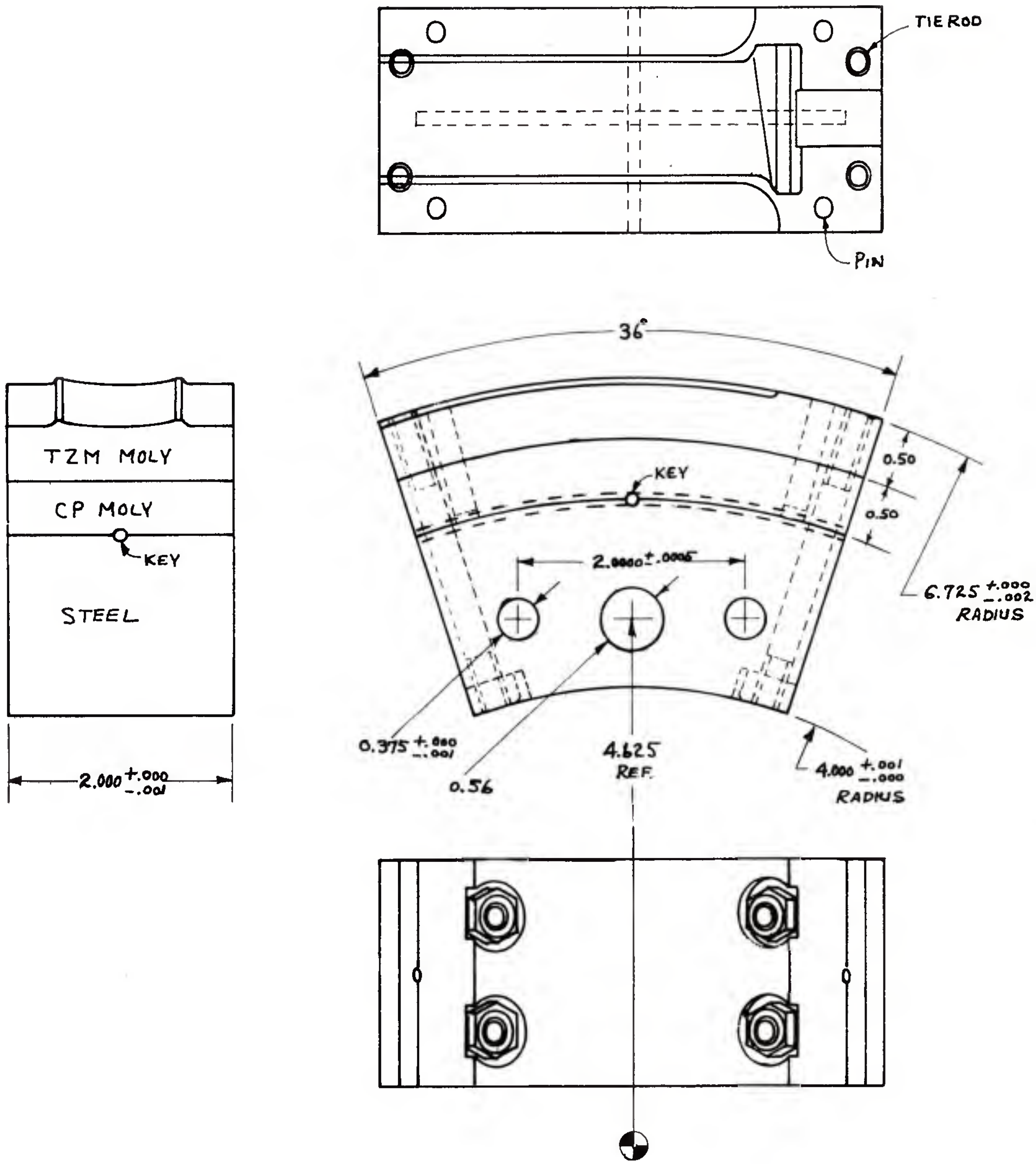



Figure 12. Improved Die Design Used for Phase I Blade Manufacture

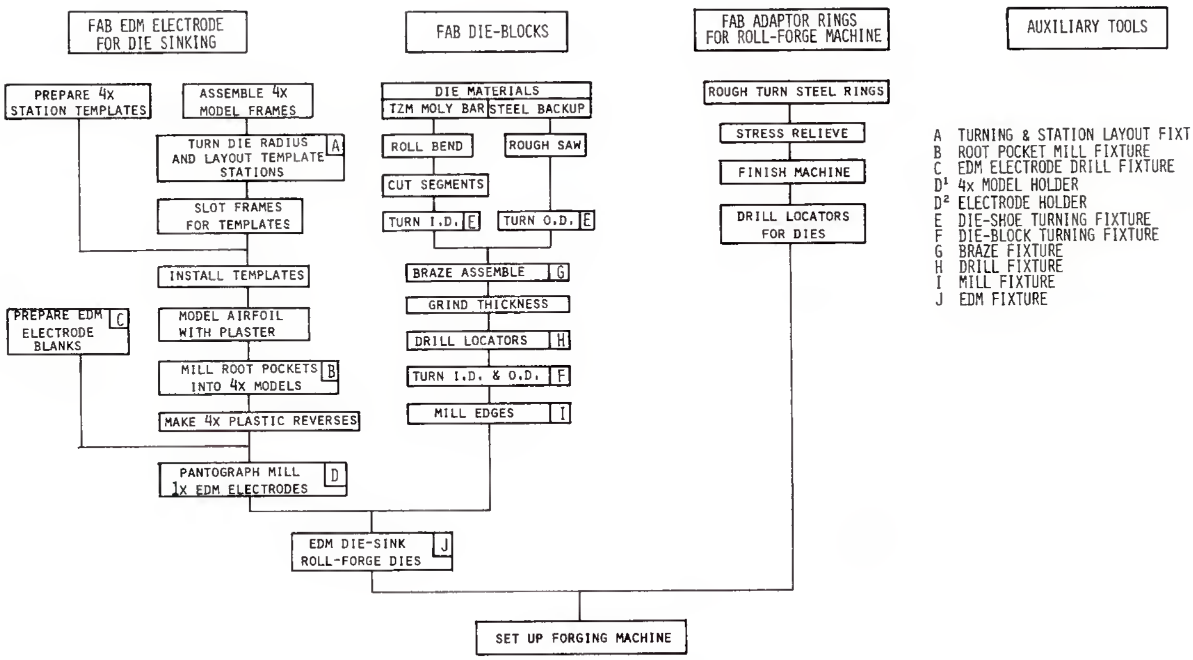



Figure 13. Flow Chart for Roll Forging Die Fabrication

blend smoothly with the templates. Figure 16 shows how the tooling balls were used to set the compound angles of the root pocket relative to stacking axis of the airfoil. The root pockets were then machined into the plaster models with an end mill. The next modeling step was the molding of plastic reverses against the curved faces of the plaster models. From the plastic reverses shown in Figure 17 EDM electrodes were profile milled using a Gorton 3D pantograph milling machine and are shown in Figure 18. Special fixtures were used to position the models and EDM electrodes to retain the location relative to the locating pins on the die blocks.

The second line of tooling activity was fabrication of the molybdenum alloy die faces and the steel support blocks. Reference to Figure 13 shows the sequence of operations used. The TZM molybdenum bar was isothermal roll formed to a 6-inch radius by the three-roll bending operation shown in Figure 19. The curved bar was cut into 36 degree segments, machined and brazed to the steel support blocks. Thickness grinding to 2.000 $\pm$ 0.001 inch and drilling of the holes for the locator pins by means of a special drill fixture, established fixture location for all subsequent machining operations including the EDM die sinking.

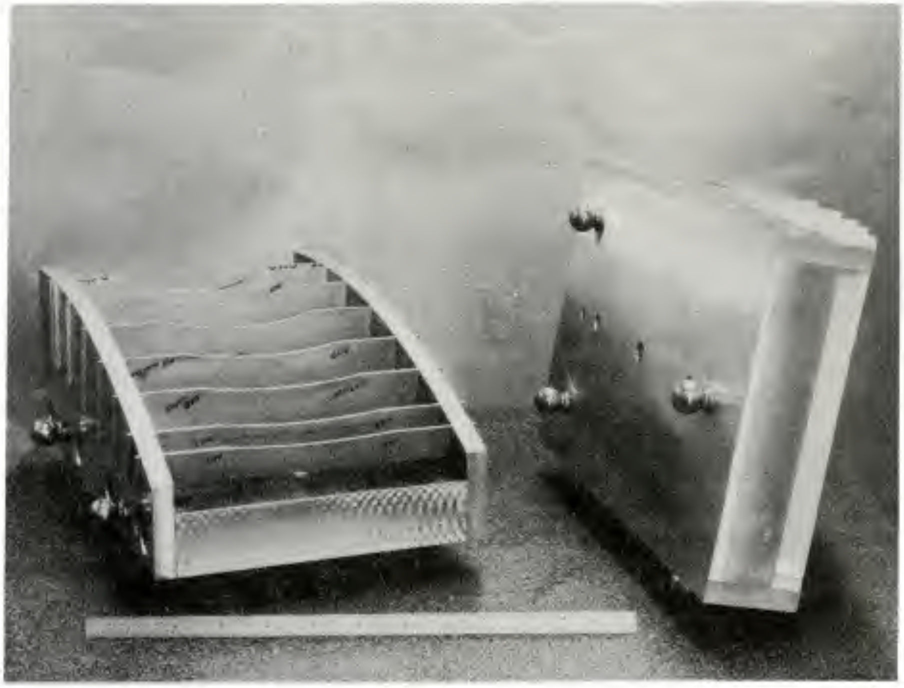


Figure 14. 4X Model Frames With Station Templates Installed (#76-4843)

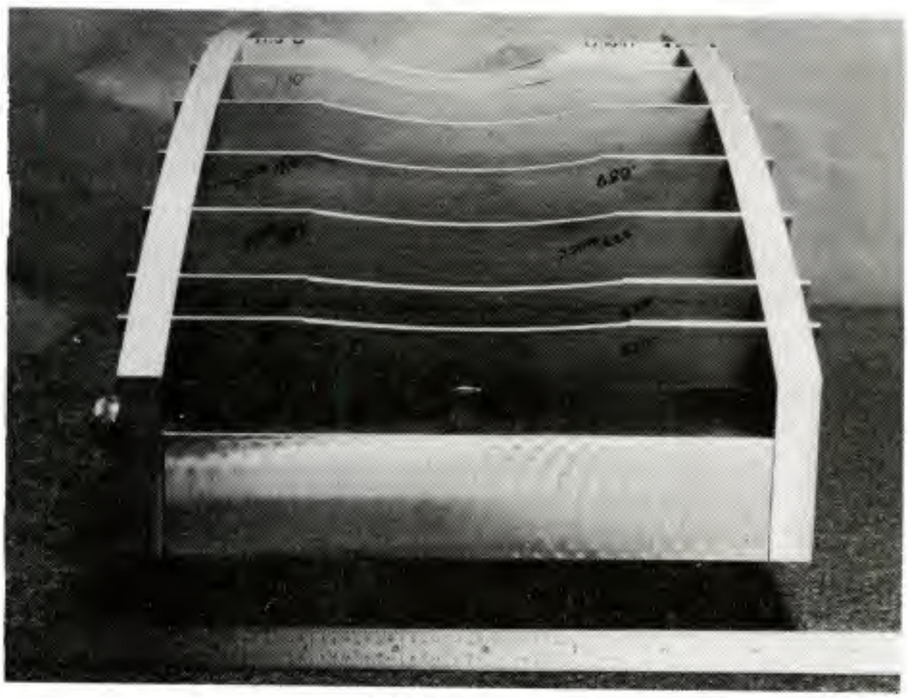


Figure 15. 4X Model Frame of Die for Roll Forging Suction Side of T55 Compressor Blade (#76-4844)

Figure 16. Milling Root Pocket in 4X Plaster Model (#76-5319)

Figure 17. Plastic Model Reverses; Four Times Actual Size (76-6095)

Figure 18. EDM Electrodes for Roll Forge Die Sinking (#76-6094)

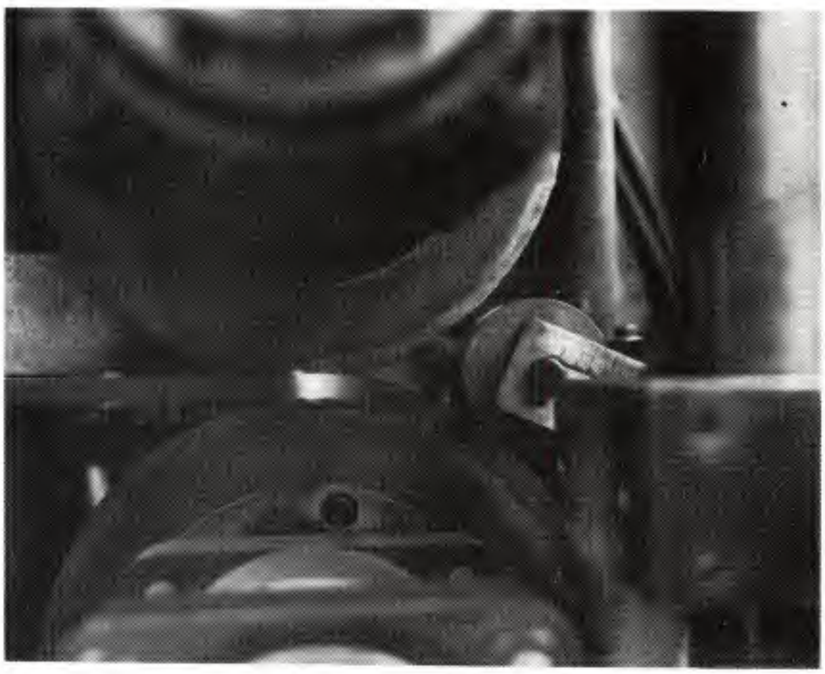


Figure 19. Isothermal Roll Bending of TZM Molybdenum Tool Facings (#75-1515)

EDM die sinking was done with a two posted die set (with insulative bushings) that controlled the position of the die relative to the EDM electrode. The electrode material found best suited for electric discharge machining of molybdenum alloys is Poco Grade C-3 graphite containing copper. The machine used was an Eltee Pulsitron Model TR20/EP30. The best machine parameters for roughing were electrode at negative potential, with 12 microseconds ON and 25 microseconds OFF. For finishing the ON time was reduced to 6 microseconds where a surface finish of approximately 30μ inch RMS was achieved. Die set No. 1 after die sinking, is shown in Figure 20.

The steel rings shown in Figure 21 were made to accommodate up to ten dies around the periphery. Each die was held in position by means of two locating pins and a tie rod. For the forging work of Phase I one die set was used and the remaining spaces around the adaptor rings were filled with steel dummy blocks. Figure 22 shows the second die set and Figure 23 shows a partial set-up in the roll forging machine.

### 3.3.3 Tool Proofing and Modification

Tool proofing involved dimensional and functional checks of the dies. As a result of this proofing, modifications were identified to solve certain problems. First, modifications were made to decrease the temperature at the interface between the molybdenum facing and steel. Second, it was necessary to add enclosures to provide protective atmosphere for airfoil roll forging. And, third, certain improvements were made to the feeder system for root upsetting.

Airfoil contour measurements made at Station L-L (see Lycoming drawing in Section 3.9) of the first die set indicated the modeling and EDM die sinking methods being used would be satisfactory for producing the envelope needed to meet the blade tolerance goals of Phase I. The measurements were obtained by cold rolling a lead workpiece between the dies:

| Airfoil Thickness at: | Nominal | Actual |
|---|---|---|
| 1) 0.030-inch gage points at leading and trailing edge. | 0.0264/0.0200 | 0.023/0.019 |
| 2) Maximum airfoil thickness | 0.0792 | 0.075 |

Allowing 0.002 to 0.005-inch for flash, the measurements indicated the dies were within the airfoil tolerance band on the drawing.

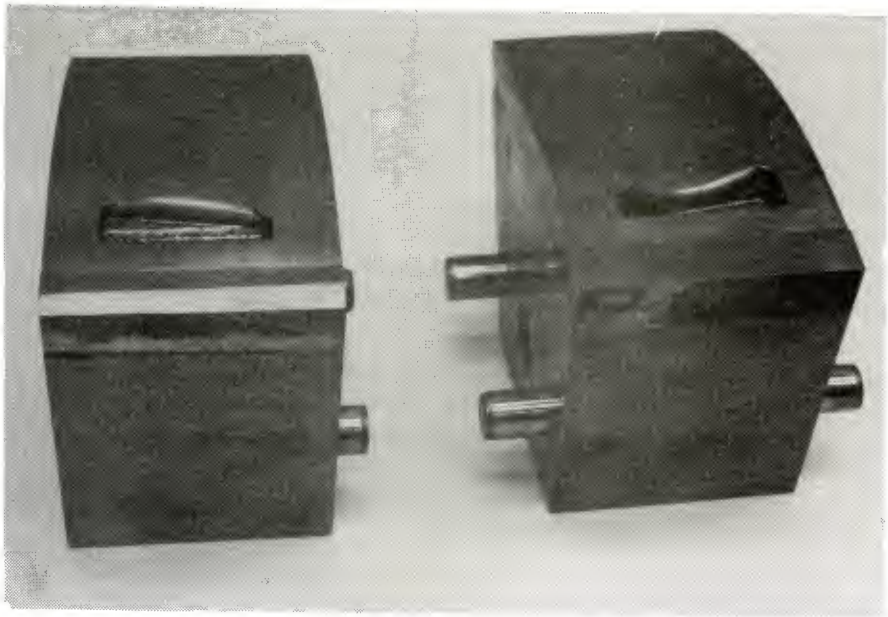


Figure 20. Die Set No. 1 (#76-6543

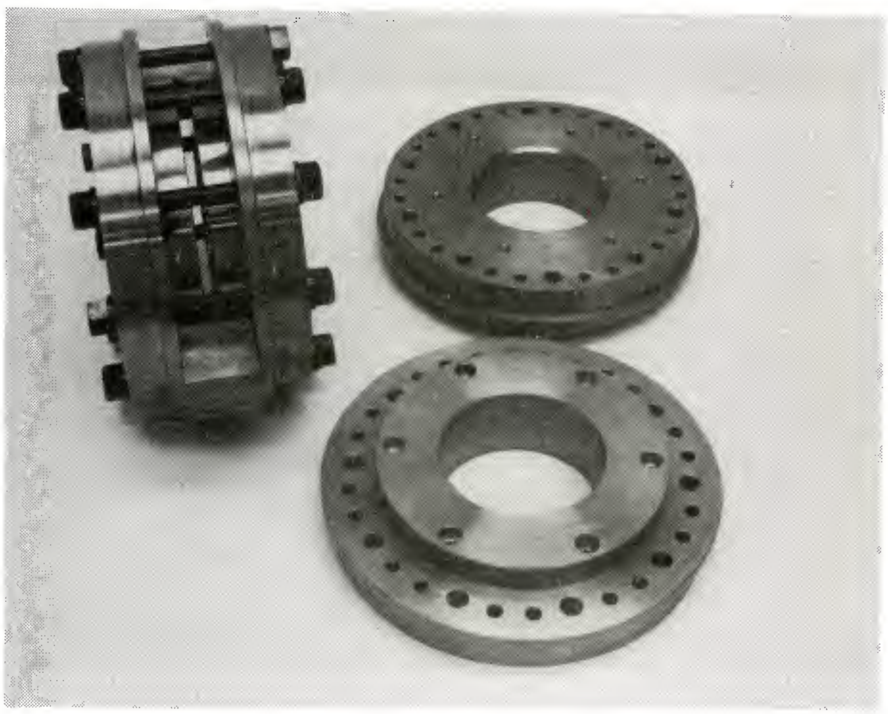


Figure 21. Roll Forge Die Holder Adapter Rings (#76-6096)

Figure 22. Die Set No. 2

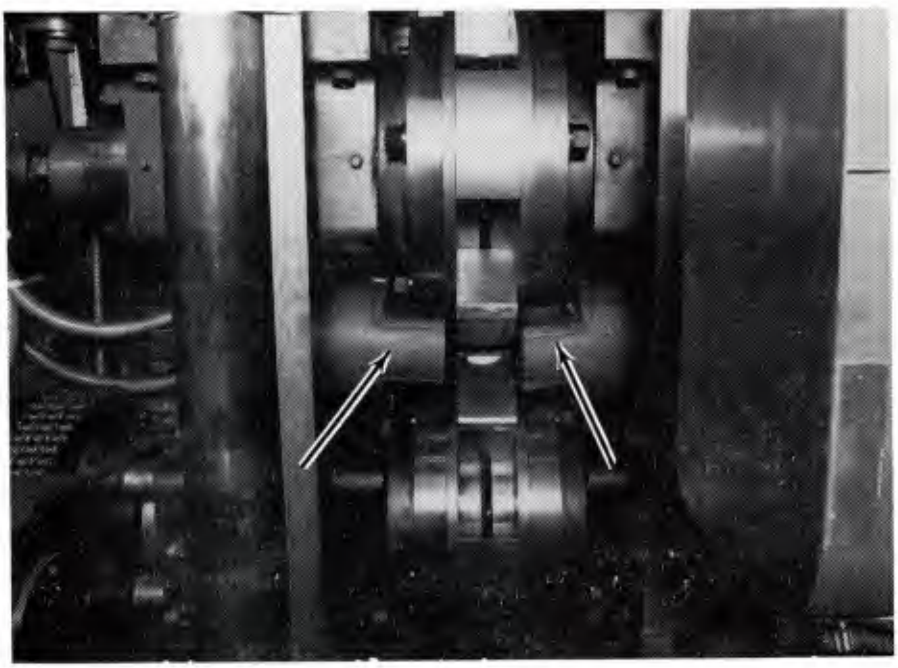


Figure 23. Die Set Installed in Roll Forging Machine (#76-6618)

The first forging runs with Die Set No. 1 showed that we had a powerful method for thermal matching of the dies to the workpiece. Optimum matching is produced when the current required to heat the workpiece to the desired forging temperature heats the surfaces of the dies to a temperature at which there is no chilling of the surface of the workpiece. Proper matching greatly increases die life. The design criteria for the first die set were to minimize the mass of the molybdenum facings and to maximize the thermal and electrical resistance at the interface between the molybdenum facings and the underlying steel support blocks. These conditions produced a workpiece temperature of 1950°F and a die face temperature of 1850°F to 1900°F. This was a most welcome result even through remelting of the brazement occurred at the molybdenum/steel interface.

The die set was modified by placing a 0.5-inch thick layer of unalloyed molybdenum between the TZM facing and the steel support block. This change achieved the desired result of retaining the temperature of the TZM facings to above 1850°F, while reducing the temperature at the molybdenum to steel interface.

Forging trials were performed with the modified die set. Three alloys were used as feedstock, chosen on the basis of increasing difficulty in forging. Trial blades were roll forged from A70 titanium, AISI 1018 steel and AM-350 alloy. Full root fill and excessive flash formation were achieved with the very plastic titanium alloy at a 1650°F forging temperature. The forging temperatures for the mild steel and AM-350 blades was 1650 and 1950°F, respectively. With the steel blades good airfoil was achieved and flash control was improved, however root fill was poor. The forging procedure used for these blades was based on the concept of continuous roll forging, i.e., to start at the blade tip and roll toward the root and to dwell when the root platform of each die becomes colinear with an imaginary line between the centers of rotation of the two dies. With the dies thus stationary, the feed force was increased causing metal to move into the root pocket. The titanium alloy moved very easily at a feed force of 4200 pounds, and completely filled the root pocket. The mild steel feedstock, having lower room temperature strength, buckled under the same load resulting in only partial fill of the dies. The high force (6000 lb) required for AM-350 worsened the buckling which was compounded by vertical deflection of the feed nozzle. As a result much of the feed force was dissipated against the back edge of the dies causing the root fill to be poor. Another problem was poor alignment of the root platform surfaces on opposite sides of the airfoil. These results supported other data indicating that root formation should preceed airfoil rolling, and that the rolling direction should be from root to blade tip. The following factors supported this conclusion: The following factors supported this conclusion:

- Critical alignment of the root platform could best be achieved by positioning the dies initially against angular stops rather than attempting to control position after rolling the length of the airfoil.

- Airfoil rolling should follow root upsetting because the root upsetting force tends also to extrude an additional short length of constant section airfoil through the stationary dies. Subsequent rolling from root to tip would correct this defect.

Additional conclusions drawn from this work were:

- Heat treatment of the AM-350 feedstock to a higher yield strength would be required to avoid buckling of the preform under the compressive feed forces needed for root upsetting.

- Additional machining was needed on the dies outside of the flashlands to provide the necessary clearance for flash formation during airfoil roll forging.

- Exclusion of air would be desirable during airfoil roll forging to prevent burn-up of the graphite forging lubricant and to protect the die faces from oxidation at the temperature required to forge AM-350.

Following the above work the next set of dies were fabricated. This set was basically the same as the modified first set, except for the method of attachment of the molybdenum facings in the steel support blocks.

1. Tantalum alloy (90TA-10W) dowels were used to pin the outer TZM facing to the underlying CP molybdenum layer.

2. Transverse and circumferential slots and keys arranged in a cruciform pattern were incorporated to position the molybdenum facings onto the steel support blocks.

3. The molybdenum facings were held in place by means of tantalum alloy rods (90Ta-10W) which extend completely through the assembly at each corner. The rods are threaded into holes tapped through both molybdenum layers

This method of attachment was designed to provide precision location of the die facings and to allow for unrestrained thermal expansion at the molybdenum to steel interface. Extensive use of these dies proved this arrangement to be very stable and reliable. This die set complete with flash clearance gutters on each side of the airfoil and with slots for injection of feedstock into the root pockets is shown in Figure 22.

During preliminary airfoil roll forging trials in AM-350 alloy it was learned that a protective atmosphere would be required to prevent burn-up of the forging lubricant and to protect the dies from oxidation. This new requirement was due to two factors: (1) the 200 degree higher temperature needed for forging AM-350 as contrasted with Ti6Al4V alloy where isothermal roll forging can be performed in air; and (2) the higher temperature and the slower cooling rate of the die facings due to improved thermal and electrical matching which was achieved with the multilayered dies.

An attempt to provide protective atmosphere through localized purging was made by installing purge nozzles on each side of the dies. These nozzles can be seen in position in Figure 23. They contain honeycomb structure in the ends adjacent to the dies that serve to straighten out the flow of the purge gas and provide more uniform coverage of the dies. A forging temperature feedback signal from the workpiece was obtained by sighting with an optical pyrometer along the axis of the right-hand (outboard) purge nozzle.

The localized purge approach reduced oxidation, however the results showed that a total atmosphere enclosure would be needed to fully resolve the problem. An atmosphere enlcosure was fabricated and is shown installed in Figures 24 and 25. The enclosure consisted of two horizontal hour-glass shaped steel plates, each with a rectangular window, clamped from each side against the upper and lower die adaptor rings, and against vertical steel end bars of the same thickness as the adaptor rings at the left and right edges. The vertical steel end bars and the side plates were fixed in position, while both adaptor rings were free to rotate and move vertically as the dies rotated and closed during the forging operation. To avoid electrical shorting, the vertical end bars were insulated from the adaptor rings with Teflon pads, and the side plates were insulated with plasma sprayed alumina where contact was made with the adaptor rings and the vertical end bars. The dies rotated into position for the start of roll forging can be seen through the Pyrex window in Figure 24. During the forging operation AM-350 barstock was force fed from the nozzle which is visible at the right side of the window, and the forged blade was withdrawn under tension toward the left.

The exit side of the enclosure is shown in Figure 25. The rectangular opening in the vertical end bar was used for removal of the forged blades. The blade tensioning device is shown penetrating a seal gland in a Plexiglas cover plate. The front and rear coverplates can be seen on each side of the vertical end bar. The purge gas (argon) was introduced by means of two tubes penetrating the rear coverplate.

During establishment of parameters for root upsetting (described in Section 3.6) it became apparent that changes were needed in the force feed system and in the procedure used for die synchronization.

The feeder system which had been used up to that time, had been built prior to this program and was designed to feed barstock in 10-foot lengths. Work in Phase I showed this feed system to be inadequate for blade forging because of sliding friction of the push rod which was excessive at the low feed forces required for blade airfoil roll forging, and because of excessive elasticity at the high forces needed for root forging.

A new feeder which is shown in Figures 26 and 27 was designed and built especially for blade forging. It has a short stroke and applies force directly to the end of the blade preform by means of a hydraulic ram. The hydraulic ram, guide box and nozzle are attached rigidly to the vertical rail at the inlet side of the dies. When the dies are opened at the conclusion of the root forging operation, the feeder assembly and the forged root are moved upward by means of the small pneumatic ram shown in Figure 25, thus clearing the forging from the pocket of the lower die and facilitating its removal.

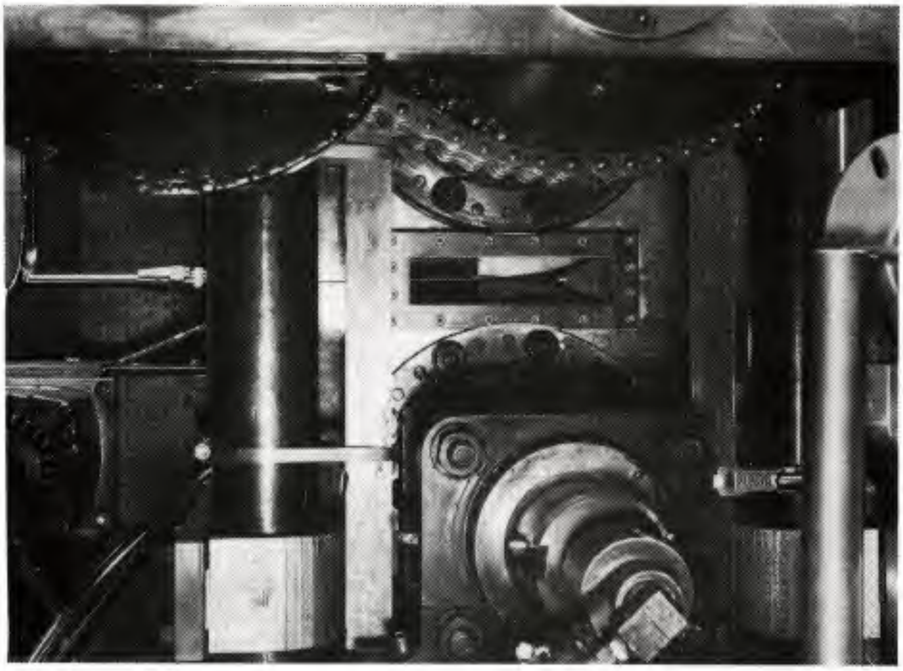


Figure 24. Set-Up for Compressor Blade Roll Forging (Side View) (#77-2118)

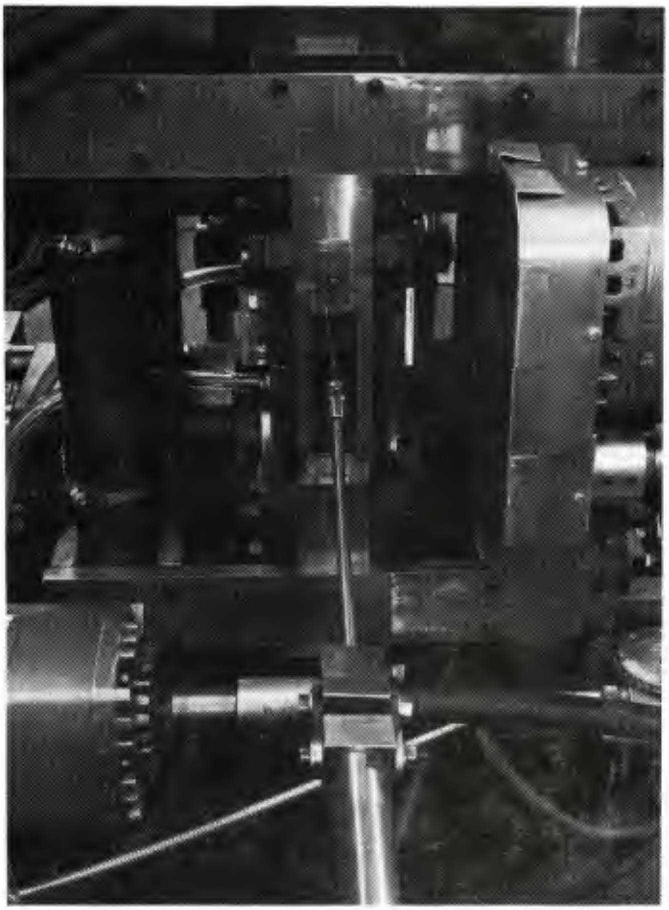


Figure 25. Set-Up for Compressor Blade Roll Forging; View of Exit End (#77-2119)

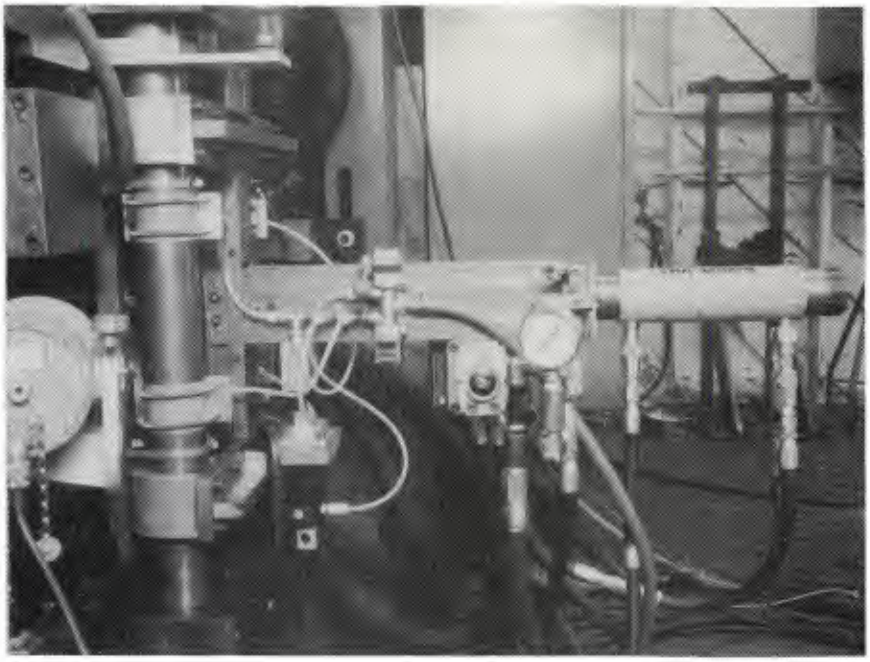


Figure 26. Force Feeder for Blade Forging; Side View

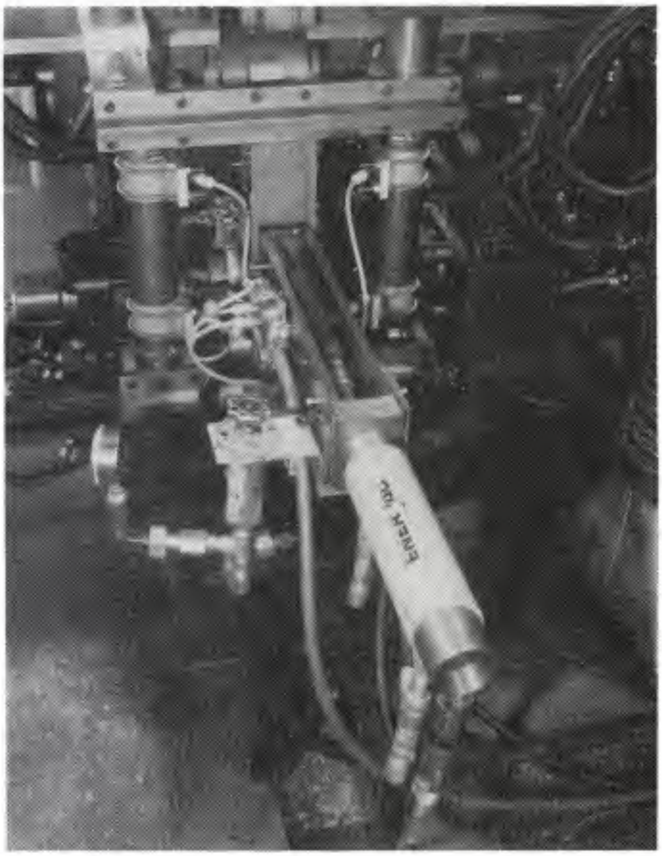


Figure 27. Force Feeder; Top View

The ram and pusher assembly of the feeder are shown in Figure 28. The pusher, machined from A6 tool steel, consists of a 0.250 x 0.500 inch tip, which is the same size as the blade feedstock. The slender tip of the pusher is supported from buckling by containment within the guide box and nozzle. The other end of the pusher has the cross section of a H-beam and is stable without support. The feeder has both force and rate controls and a transducer is installed on the ram to provide a signal for recording feed force as function of time.

The relationship of the feeder assembly to the rest of the forging machine is shown schematically in Figure 29. This figure also shows the angular position stops which also were incorporated into the machine during this period to facilitate root forging. Angular position stops were needed to precisely synchronize the dies to within 2.5 minutes of angle to achieve the required alignment of the root platform of the forging, and also to resist the 65,000 lb-in. torque generated by the feed force. To meet these requirements the angular position stops had to be both precise and strong. As illustrated in Figure 29, the stops consist of two heavy steel pawls which pivot and engage one side of the slots in the adaptor rings. The position of the fulcrum of each pawl could be adjusted horizontally to establish the correct angular alignment.

After these changes were made root platform alignment was achieved in just two forging trials and root formation adequate to provide the necessary machining envelope was achieved after the sixth forging trial.

The final die set modification in Phase I was made to correct a weakness in the previous design that was detected during the finish airfoil roll forge operation. After finish roll forging several blades, it was observed that the blades were overthickness near their tip end. Measurement of the dies revealed this change largely was caused by compressive deformation of the underlying steel support block near the blade tip end of the dies. The temperature build-up and the corresponding reduction in strength in the steel near the end of a airfoil roll-forge pass caused the steel to yield under the forging load. To reduce the temperature build-up the mass of the steel support block was increased three fold from 36 to 108 degrees of arc. The same molybdenum facings were used as before, but were now attached to the middle 36 degrees of the support block. Also, the steel was changed from mild steel to SAE 4130 low alloy steel tempered at 1000°F to provide additional strength. This die set was completed near the end of Phase I but has not been completely evaluated.

## 3.4 TASK 4 - PREFORM

The principal factors in the design of a blade preform for isothermal roll forging are blade producibility, the effect of configuration on die life, and low cost. Related to all three are the subfactors: configuration, heat treatment, and surface condition.

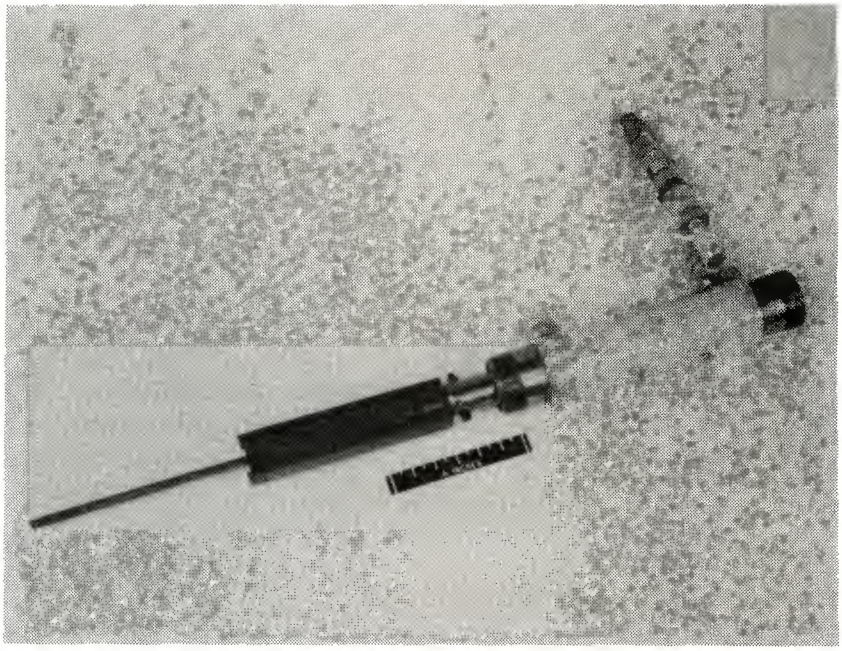


Figure 28. Ram and Pusher Assembly of Feeder

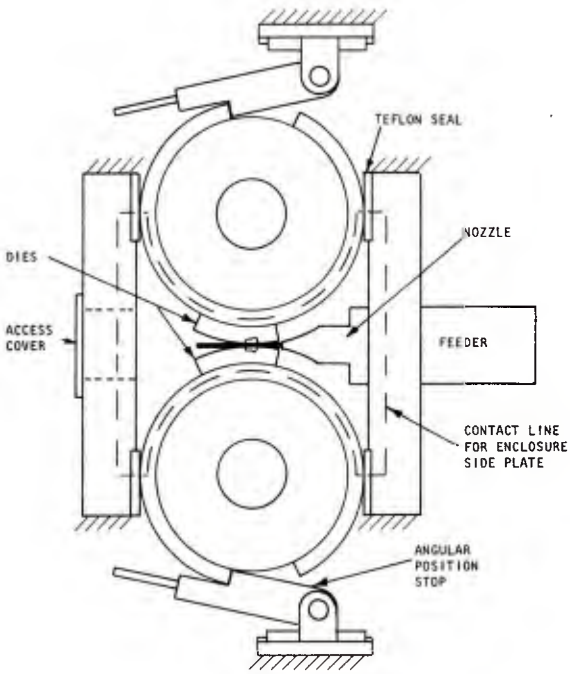



Figure 29. Schematic of Roll Forge Machine Showing Angular Position Stops and Workpiece Feeder Arrangement for Root Forging Operation.

Preform configuration was established on the basis of:

1. Section area of root and airfoil.
3. Resistance to buckling under compressive feed forces.
4. Avoidance of point and line contacts with dies.
5. Material availability
6. Cost of manufacture.

To minimize cost the first choice was to use a constant section preform of a standard mill shape, i.e., circular, square or rectangular section. The section area of the preform was initially set at 0.1 square inch. This choice being a compromise to minimize the metal gathering required when upsetting the root, and the thinning required and the resulting flash formation when roll forging the airfoil. (The cross-section areas of the root and airfoil of the rough forged blade are approximately 0.13 and 0.07 square inch, respectively). The next consideration was selection of the optimum geometry of the section to avoid forging laps and to resist buckling under compressive loading. The circular section is most resistant to buckling but tends to lap formation because the airfoil spreads at a faster rate than does the root. Conversely a wide rectangle of the same section area does not form laps, but buckles due to a much smaller radius of gyration. An intermediate section of 0.25 by 0.50 inch was found to avoid the edge lapping, and after heat treatment to high strength, to resist buckling. Obviously this section also is desirable from the standpoint of availability and cost.

Precise dimensions of the section do not appear to be critical. Preforms with variations in thickness or width of 0.030 inch perform equally well provided a close fit (0.005 in. maximum clearance) in the supporting feeder nozzle is maintained.

A problem encountered in Phase I was die marking which occurred when initial contact was over a very limited area between the preform and the molybdenum forging dies. When initial contact is made the dies and preform normally are at a temperature of less than 500°F, under which condition line or point contact cause localized deformation of the dies because of the higher cold hardness of the preform. This problem was resolved by modifying the rectangular section of the preform as shown in Figure 30. The radius and offset were designed to fit the die contours at airfoil station N, (see Section 3.9) where initial contact is made for the root upsetting operation. The 1.00 inch radius was made by lathe turning on a simple fixture, and the 1.80 inch radius by coping with a 1.0 inch end mill inclined to a 14 degree angle from perpendicular. For large quantity requirements the section would be cold rolled at minimal unit cost.

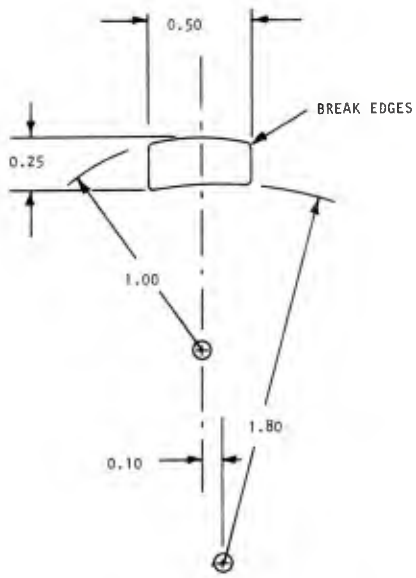



Figure 30.

Cross Section of Blade Preform as Viewed From Tip End of Blade

The metallurgical structure of the preform does not appear to be critical in regards to metal flow during root upset and airfoil rolling because these operations are done at 1950°F where the effects of prior structure rapidly disappear. Both solution annealed, and hardened and tempered AM-350 preforms roll forged equally well. However, because of the high compressive force required for root upsetting (10,000 lb on a 0.125 square in. section) it was necessary to harden and temper the preforms to avoid plastic deformation and buckling in the short unsupported portion between the feeder nozzle and the dies. The standard solution treatment at 1710°F followed by subzero cool (-100°F) and temper at 100°F was found effective to solve the buckling problem.

The surface condition of the preform should be rough enough to obtain good adhesion of the graphite forging lubricant, but free of machining marks that could cause die marking. Etched, sand blasted or tumbled finishes are all satisfactory.

## 3.5 TASK 5 - PROPERTIES OF ROLL FORGED AM-350

A roll forged compressor blade will contain a wide range of thermo-mechanical conditions. Temperatures will vary to a small extent in isothermal roll forging, but the principal difference from point-to-point will be in the amount and direction of metal flow. Flow at the root injection step will be approximately at right angles to the length of the blade whereas the airfoil roll forging will be largely longitudinal with some lateral flow. From another viewpoint, the 0.25 inch stock is reduced to 0.008 inch (96.8%) at the minimum TE thickness, to 0.090 inch (64% reduction) at the airfoil maximum thickness, but only redundant work is applied to some portions of the root section.

An arbitrary selection of roll forge conditions was made for evaluation at Avco. Three reductions of approximately 24, 38 and 60 percent were made by isothermal rolling for evaluation. Four rolling temperatures were used in the material preparation.

### 3.5.1 Preparation of Materials

The isothermal rolling set-up used to prepare the material for evaluation is shown in Figure 31. The AM-350 strip can be seen emerging from the force feeder at the right. Temperature sighting at the point of maximum temperature provided the signal for automatic temperature control. Front tension was applied to maintain straightness that was good as can be seen in Figure 31. The tension was nominal and in the range of 200 to 300 pounds of tension load for the different reductions. The reduction was controlled by mechanical stops to maintain roll gap. All rolling was performed with the dry graphite lubricant applied by spray.

Sixteen feet of 0.350 x 1.3 inch AM-350 material purchased from Utica Forge was isothermally rolled. The rolling reductions were 22-25%, 36-40% and 58-61%. Rolling temperatures were 1850, 1900, 1950 and 2000°F. Table 1 shows details of the material sent to Avco.

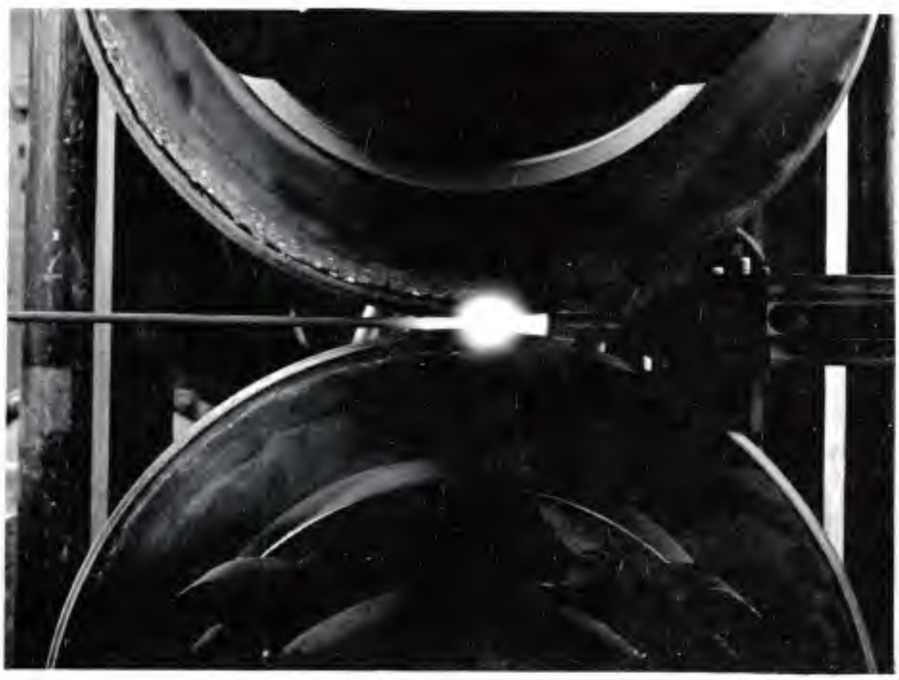


Figure 31. Isothermal Rolling of AM-350 Strip (#77-6057)

Table 1

Isothermal Rolled AM-350 Barstock Sent to Avco

| Quantity | Rolling Temperature (°F) | Reduction (%) | Code |
|---|---|---|---|
| 1 | As-Received Condition | | A |
| 1 | 1850 | 22 | B1 |
| 1 | 1850 | 36 | B2 |
| 1 | 1850 | 58 | B3 |
| 1 | 1900 | 22 | C1 |
| 1 | 1900 | 37 | C2 |
| 1 | 1900 | 60 | C3 |
| 1 | 1950 | 24 | D1 |
| 1 | 1950 | 39 | D2 |
| 1 | 1950 | 61 | D3 |
| 1 | 2000 | 25 | E1 |
| 1 | 2000 | 40 | E2 |
| 1 | 2000 | 61 | E3 |

### 3.5.2 Evaluation of Isothermal Rolled AM-350

The 13 samples listed in Table 1 were examined at Avco by microstructure evaluation in the as-received and direct aged (1000°F for 3 hr) condition. All sections for microstructure evaluation were made in the longitudinal direction. These were supplemented with transverse sections for material rolled at the highest and lowest temperatures and reductions, i.e., the 1850°F, 20 and 60% reductions, and the 2000°F, 20 and 60% reductions.

The microstructure of the as-received barstock, specimen A (Table 1) was found to be tempered martensite with a network of intergranular continuous carbides to 500X magnification. Elongated delta-ferrite stringers were prevalent throughout the structure, but it is expected that they will be broken up during forging and will not be detrimetnal to the final product. A section of specimen A was submitted for chemical analysis, and the chemistry was found to conform to Lycoming material specification M3709, revision C.

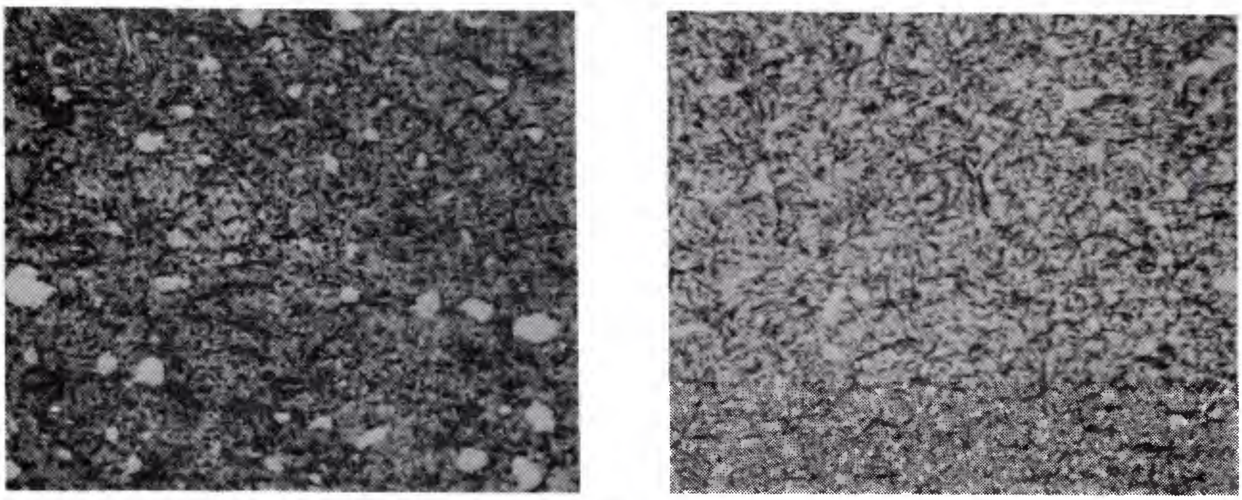
The direct aging of the as-rolled specimens was designed to reveal any anomolies regarding carbide morphology, particularly the formation of carbides on prior austenite grain boundaries. Additionally, direct aging, in tempering the martensite present after cooling from the forging temperatures, provides the contrast needed to delineate any austenite which may be present. Etching the specimens in dilute Marbles Reagent revealed a martensitic surface layer with ribbon-like austenite banding in the 20 and 40% reduced samples. The 60% reductions were sufficiently worked such that the samples were entirely austenitic. There was no evidence of heavy grain boundary carbides in any of the specimens.

Mechanical tests were performed at Avco after the as-received feedstock was solution annealed, subzero cooled, hardened and tempered per the requirements of Lycoming material specification M3709C. The heat treated feedstock was then sectioned for microstructural examination and austenite determination, and tensile testing. The results in Table 2 show that the heat treated feedstock conforms to M3709C.

Figure 32 shows the structure of the material heat treated as indicated in Table 2 in comparison with the minimum acceptable microstructure according to the Lycoming material specification M3709. Avco Lycoming concluded that the feedstock was acceptable for compressor blade material.

Post-forge heat treatment studies of the roll forged strip were made to select the best conditions for processing blades. Table 3 gives the heat treatments examined.

Microstructure studies showed that the first heat treatment, sample No. 1 in Table 3, resulted in an acceptable microstructure, as did all subsequent heat treatments outlined in this table. The conclusion here is that the post-forge heat treatment given by sample No. 1 - Harden and Temper - is sufficient for proper microstructure of the AM-350 roll forged strip.



Minimum Acceptable Microstructure as Defined by Avco Specification. Magnification: 500X

Typical Microstructure of Heat Treated Feedstock. Magnification: 500X

Figure 32. Microstructure of Heat Treated Feedstock

Table 2

Properties of Feedstock After Heat Treating*

| | UTS (ksi) | YS (ksi) | EL (%) | RA (%) | Microstructure | Hardness Rc |
|---|---|---|---|---|---|---|
| Required by M3709 | 165 | 140 | 10 | 20 | ** | 35-44 |
| Properties of Feedstock | 170 | 160 | 16 | 55 | Acceptable | 37 |

* Heat Treat: (1) Solution Anneal 1925 ± 25°F (45 min), rapid or cool.
(2) Sub-zero Cool -100°F (3 hr)
(3) Harden 1710 ± 25°F (30 min), air cool, cool to minus 100°F (3 hr), air warm.
(4) Temper 1000 ± 10°F (3 hr), air cool.

** M3709C requires the structure to be tempered martensite and small grained delta ferrite. A small amount of discontinuous carbide precipitate shall be permitted within the martensite grains or at the junction of martensite and delta ferrite. A maximum of 15 percent of retained austenite as measured by X-ray diffraction shall be permitted.

Table 3

Post-Forged Heat Treat Study of AM-350 Roll Forged Strip

| Sample Number | Heat Treatment* |
|---|---|
| 1 | L3 + L4B |
| 2 | SZC + L3 + L4B |
| 3 | L8A + L4C + L3 + L4B |
| 4 | L1 + SZC + L3 + L4B |

*Heat Treatments - as specified in Lycoming Heat Treat Specification P6000, Instruction Sheet 28.

L1 Solution Anneal 1925 ± 25°F (45 min total) + rapid air cool.

L3 Harden 1710 ± 25°F (30 min), air cool, + subzero cool (-100°F for 3 hr), air warm.

L4B Temper 1000 ± 10°F (3 hr at heat), air cool.

L4C Overtemper 1075 ± 10°F (3 hr at heat) + air cool.

L8A Equalize 1425 ± 25°F (3 hr at heat) + cool to below 70°F.

SZC Subzero Cool to minus 100°F (3 hr at temperature), air warm.

## 3.6 TASK 6 - ROUGH ROLL FORGING

Rough roll forging as established in this section describes the steps which were used to convert simple rectangular feedstock into the complex shaped preform that could subsequently be formed to the finish forged blade by a single roll forge operation. The steps used were root formation by the feedstock injection technique and airfoil roll forge. The steps were performed as separate operations because of present limitations of the feed system of the forging machine. As will be explained below, the root formation requires application of feed force at the root end whereas airfoil rolling requires application of feed force to the tip end of the blade. In Phase II it is planned to upgrade the feeder system so that root formation and airfoil rolling can be combined into a single continuous operation.

The machine set-up for blade roll forging is shown in Figure 33. The machine is a 20 ton four-posted hydraulic press with a fixed lower platten and moveable upper platten. Each platten carries a roll shaft, bearings, current collectors and a mechanical drive. The output of a 30,000 ampere direct current power supply is connected to the two current collectors on each platten by means of water-cooled copper cables. The roll drive system consists of two 3200 to 1 speed reducers with input through flexible shafts from a common variable speed motor. The heating current is controlled

Figure 33.

Machine Set-Up for Blade Forging (#76-6617)

directly by feedback from a water-cooled shunt in the secondary circuit, or indirectly by feedback from an Ircon infrared detector focused on the workpiece. A hydraulic cylinder is used to feed the work into the rolls (dies in this case) and a pneumatic cylinder is used to apply tension to the workpiece as it emerges from the rolls.

Blade forging, as demonstrated in Phase I, involved root formation by feedstock injection, followed by rough and finish roll forge passes to produce the airfoil. A simple feedstock is formed to the complex blade shape by application of external forces to the heated zone of the feedstock between the dies. Figure 34 schematically shows the force system and the sites for optical pyrometry used during blade forging. The die squeeze force causes the dies to close upon the feedstock until the descent of the upper platten is stopped by steel bars located beside each of the four posts. Two of these stops are visible in Figure 33. During the initial squeeze of the workpiece, when contact has not yet been made with the mechanical stops, the squeeze force is applied entirely to the workpiece. After engagement of the stops the squeeze force is distributed between the stops and the workpiece in a manner determined by the resistance to deformation of the workpiece. The plan in Phase I was to apply sufficient die squeeze force to ensure contact would be maintained against the stops during the root and airfoil forging operations.

The root injection force is applied to the root end of the feedstock when the dies are in the stationary root forging position which is shown in Figure 34. This compressive force upsets the metal that is heated between the dies and causes the root to be formed between the opposed root pockets of the dies. During root formation the dies are stationary and the point of closest approach between the curved die surfaces was established at 0.6 inch toward the blade tip from the root platform. This position opens each die about 5 degrees and facilitates the inward flow of metal and provides optical access for temperature control to the heated workpiece at the point labeled $\text{PYRO}_{\text{ROOT}}$ in Figure 34. During root injection, rotation of the dies is prevented by mechanical angular stops (see Fig. 29).

For blade airfoil rolling the dies are rotated in the direction indicated by the curved arrows in Figure 34. For this operation the root injection force is removed, the pyrometer target is shifted to the point labeled $\text{PYRO}_{\text{BLADE}}$, and the tip feed and front tension forces are applied. The tip feed force makes possible thickness reductions exceeding 90 percent and promotes lateral spreading of metal into the thin leading and trailing edges of the airfoil. Front tension is a low magnitude force applied at the root end of the blade that straightens the hot airfoil as it emerges from the rotating dies.

The first blade forging trials were made with Ti6Al4V feedstock. The approach taken in Phase I was first to work with titanium alloy to establish preliminary parameters, then to introduce the AM-350. Because of prior blade forging experience with titanium alloys it was felt this approach would expose the dies to a lesser risk of being damaged during the initial trials.

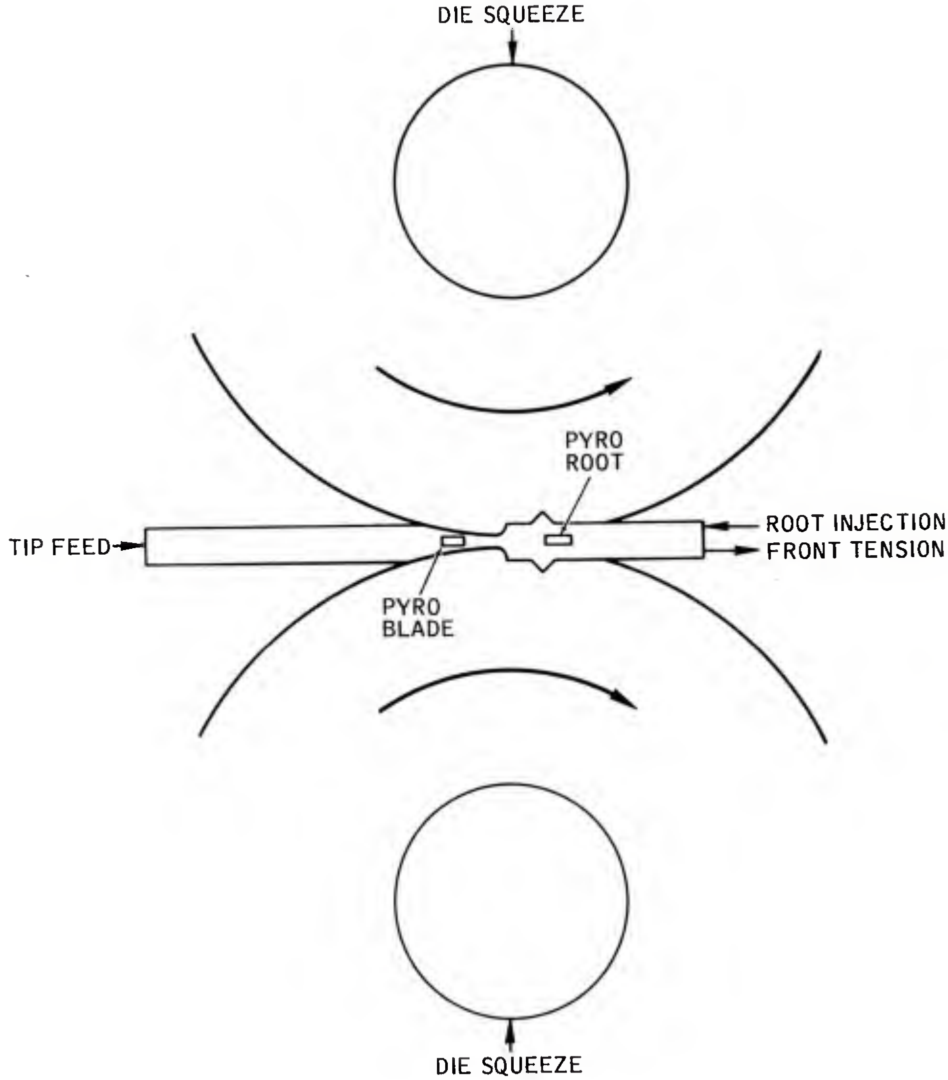



Figure 34. Force System and Optical Pyrometry Targets for T55 2nd Stage Blade Forging

### 3.6.1 Root Formation

Figure 35 shows the first root forgings produced in Ti6Al4V and AM-350 alloys. The five in the lower right are AM-350 alloys. The top row of forgings were made with a wide range of parameters, including:

- Die angle
- Temperature from 1600 to 1900°F
- Root injection force from 4000 to 8000 pounds with various controlled rates of application

The extreme plasticity of Ti6Al4V is evidenced by the forging shown in Figure 36 where extrusion occurred in both the forward direction through the airfoil shaped dies and backward through the gap between the curved dies.

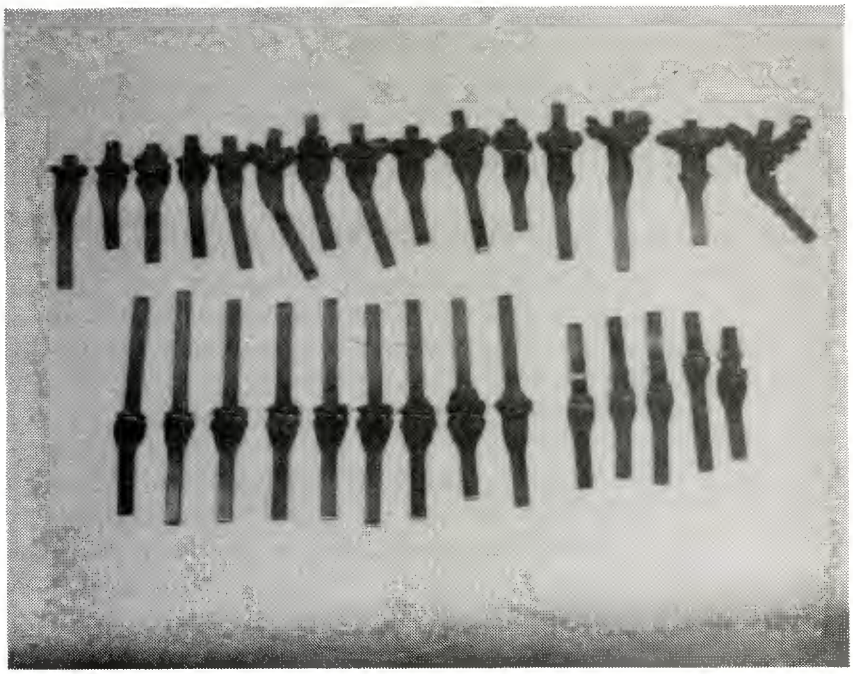


Figure 35. First Series of Root Forgings in Ti6Al4V and AM-350 Alloys

Figure 36. Trial Root Forging Showing The Extreme Plasticity of Ti6Al4V

A series of nine forgings shown in Figure 37 was made to study the effect of rate and duration of the injection force on the extent of root fill. Held constant were: 5 degree die angle; 30 seconds heat-up time prior to root injection; 1700°F workpiece temperature; and a final injection force of 6250 pounds. Variable were the initial force and the rise time to maximum force. The data for this series are presented in Table 4. As shown on the bottom line the best results were obtained using a high force for a short time interval. The reason was explained by the data in the right hand column. Slow application of force provided more time for heat to conduct axially in the feedstock, reducing its yield strength, and allowing thickening to occur behind the root pockets. Thickening caused unwanted die contact and attenuation of the force needed for root upsetting further inside the dies.

The first few trials at root formation in AM-350 alloy are shown in Figure 38. At best, the root fill achieved was only about 50 percent complete, however the formation of the transition radius and platform were good and no damage was imparted to the dies.

Figure 39 shows a root forging in Ti6Al4V alloy. Complete root fill with perfect replication of the die surfaces was achieved. Upsetting was done by impulse loading to 6250 pounds with a one minute hold time under load. The hold time was excessive as indicated by the extreme thickening of the feedstock behind the root.

In general, the root forging techniques established for Ti6Al4V alloy were found applicable to AM-350 alloy; however, a higher injection force and higher temperature, as shown in Table 5, were required to achieve full root.

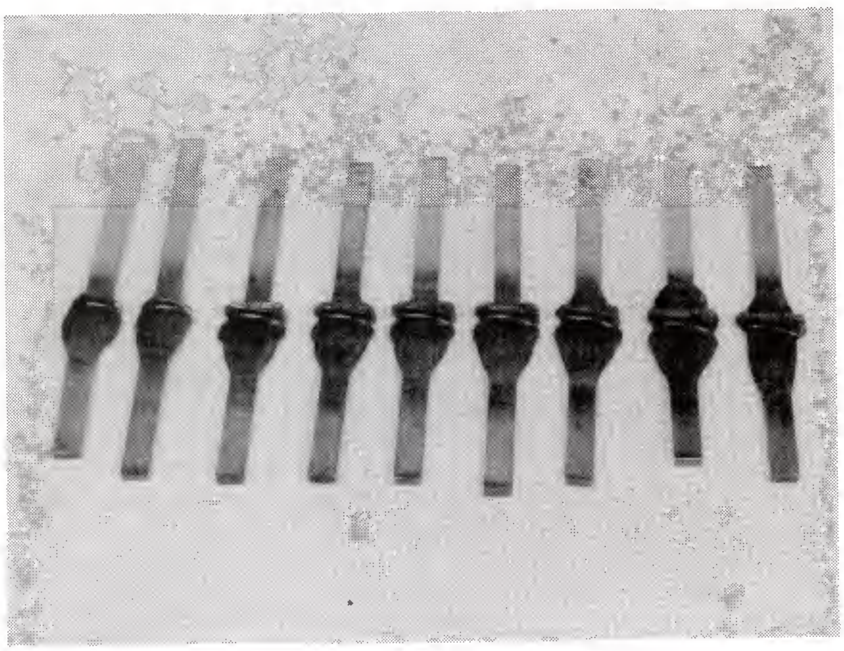


Figure 37. Series of Ti6Al4V Root Forgings Showing Effect of Injection Time on Root Fill

Table 4

Effect of Feedstock Injection Rate on Blade Root Formation

(Alloy - 6Al4V Titanium; Feedstock - 0.25 In. x 0.50 In. x L)

| Force (lb) | | Time (sec) | | Results | |
|---|---|---|---|---|---|
| Initial | Final | Rise Time From Initial to Final Force | Hold at Final Force | Root Fill Achieved (Approximate) (%) | Length of Feedstock Thickened Behind Root (in.) |
| 1250 | 6250 | 3 | 0 | 25 | 0 |
| 1250 | 6250 | 3 | 5 | 25 | 0 |
| 1250 | 6250 | 3 | 10 | 75 | .05 |
| 1250 | 6250 | 3 | 20 | 75 | .18 |
| 1250 | 6250 | 3 | 30 | 75 | .26 |
| 1250 | 6250 | 40 | 10 | 70 | .40 |
| 1250 | 6250 | 50 | 10 | 70 | .50 |
| 0 | 6250 | 0 | 60 | 100 | .40 |
| 0 | 6250 | 0 | 15 | 100 | .05 |

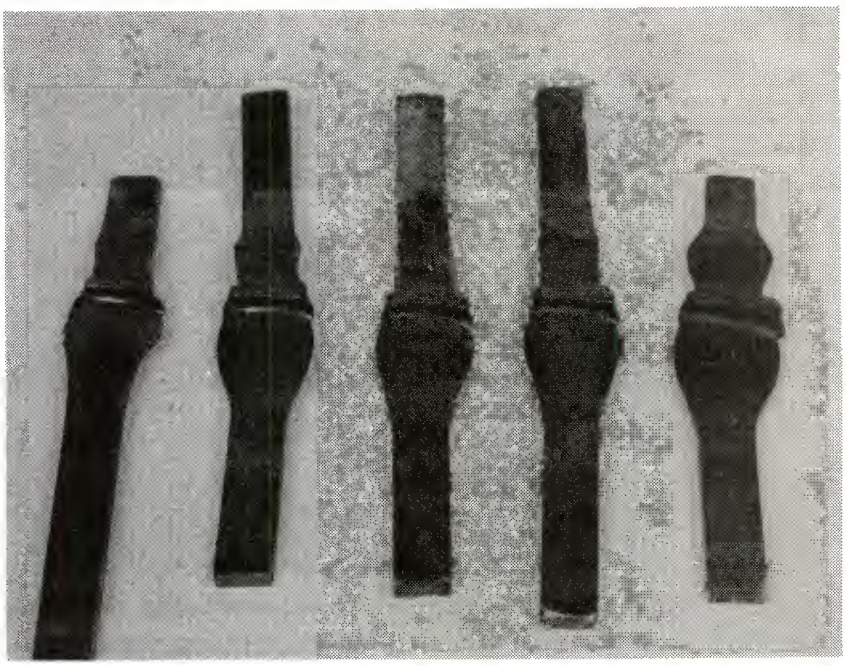


Figure 38. First Series of AM-350 Root Forgings

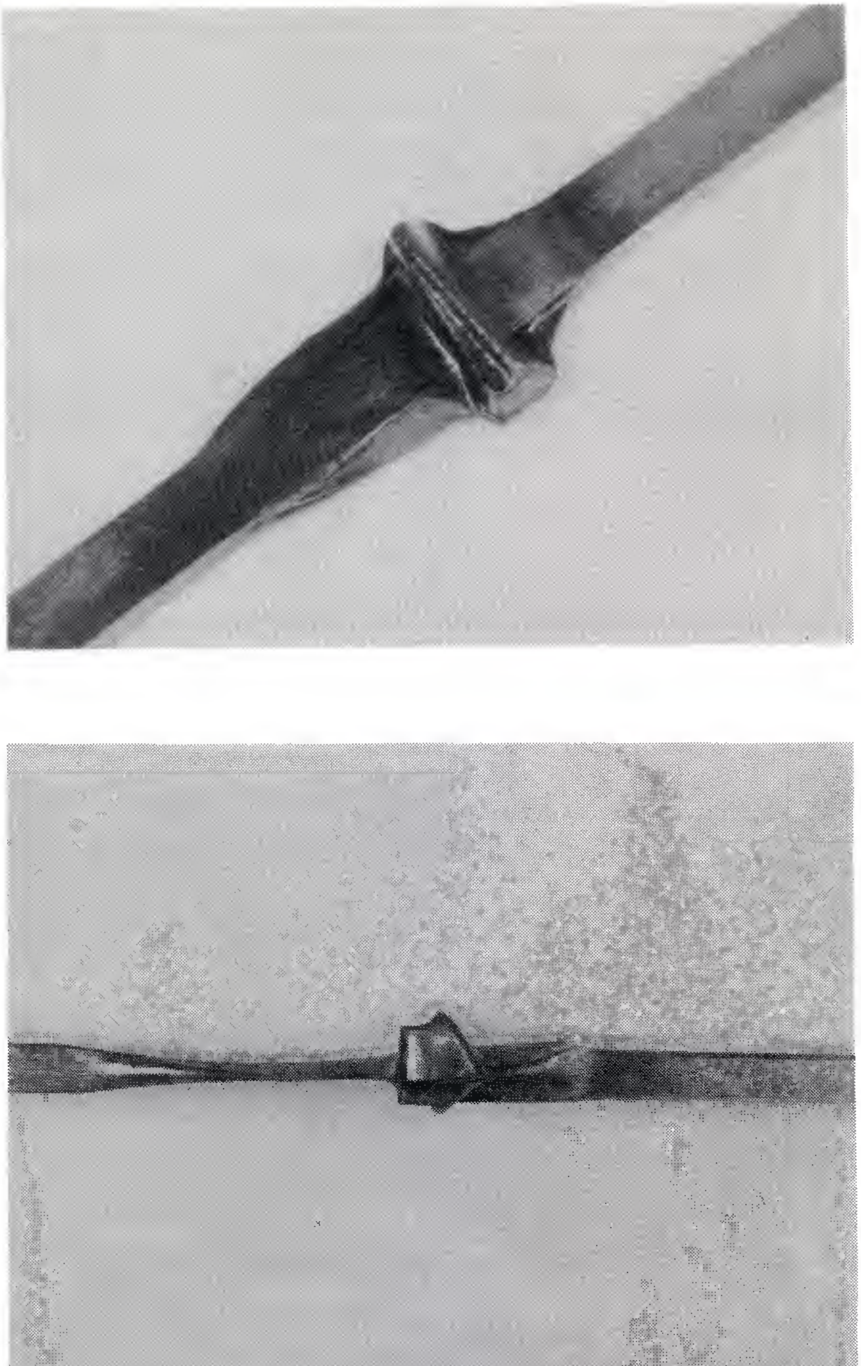


Figure 39. Root Forging in Ti6Al4V Alloy Showing Complete Root Fill

Figure 40 shows 20 AM-350 root forgings which were made by the established injection technique. The parameters of temperature, injection force, injection rate and time were varied until full root formation was achieved as shown in Figure 41. As was found during the preliminary work with titanium alloy, good results were obtained with AM-350 using a rapid application of injection force followed by a dwell at 10,000 pounds for about 15 seconds. It was necessary to heat treat the annealed AM-350 feedstock to a higher strength level (1710°F harden + subzero cool + 1000°F temper) to avoid buckling when the high compressive injection force was applied.

Table 5

Comparative Root Forging Parameters for Titanium and Steel

| Alloy | Temperature (°F) | Injection Force (lbs) |
|---|---|---|
| 6Al4V Titanium | 1,700 | 6,250 |
| AM-350 | 2,050 | 10,000 |

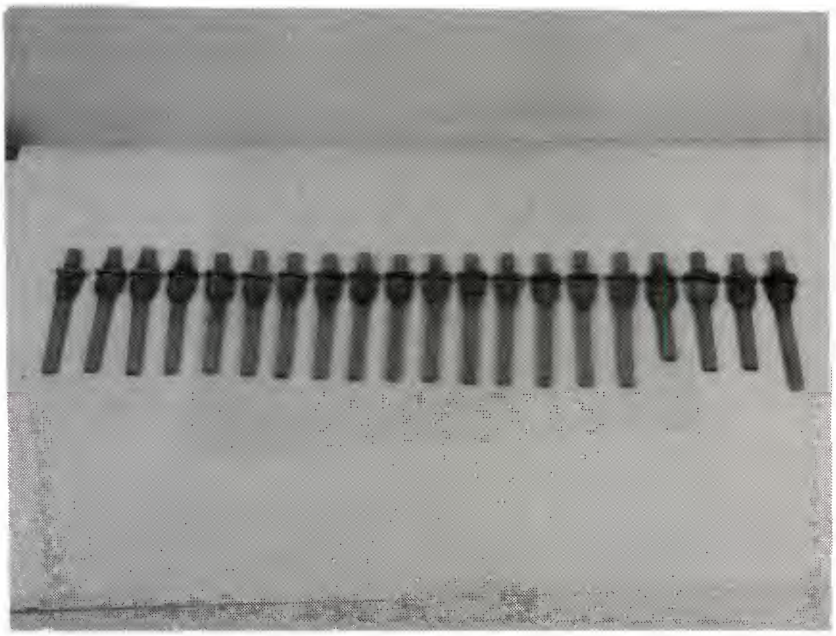
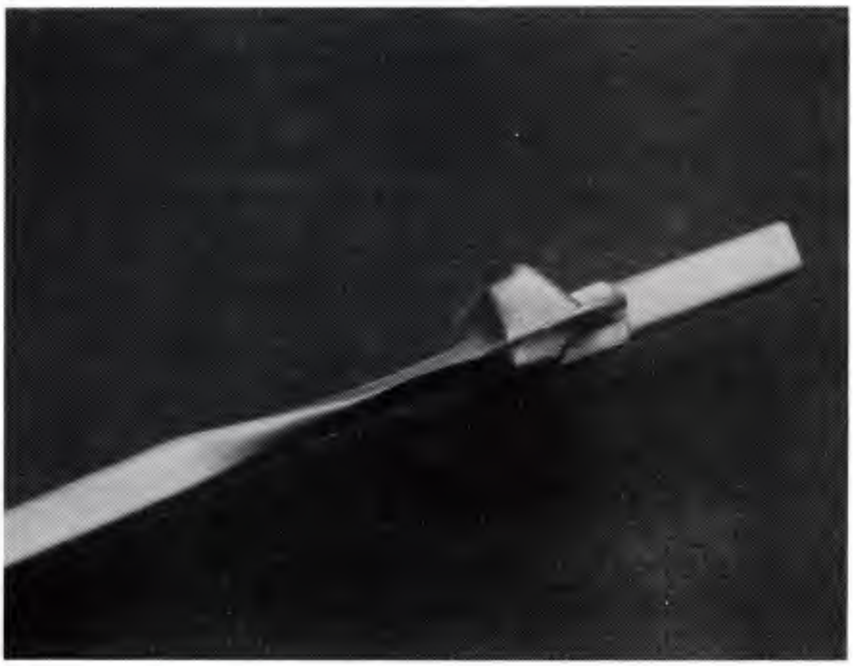


Figure 40. Second Series of AM-350 Root Forgings

A.



B.

Figure 41. Root Forging in AM-350 Alloy Showing Complete Root Fill

From the above parametric study a set of force and temperature profiles, shown in Figure 42, was selected that was most effective in root formation in AM-350 alloy. The selected process is divided into heat-up, root formation and cool-down segments. After minimum force die contact is made with the feedstock (1500 lb is the dead weight of the upper head, platten and shaft assemblies of the forging machine) the heating current is initiated and increased linearly until a forging temperature of 1950°F is attained in about 30 seconds. A force programmer then is started that controls the following sequence of events: (1) the die squeeze force increases to 40,000 pounds in 20 seconds while the optical pyrometer sighting the workpiece maintains the forging temperature, the temperature is adjusted upward to 2000 °F; and (2) the root injection force is applied rapidly to a level of 10,000 pounds for approximately 25 seconds while 1.20 $\pm$ 0.03 inch of feedstock is injected into the dies. The heating current is turned off, the forces removed and the dies opened. This process for root formation was selected as best during the prototype production run of 55 forgings shown in Figure 43. The typical root forging resulting from the selected process parameters is shown in Figure 44.

### 3.6.2 Airfoil Roll Forging

Isothermal roll forging of the blade airfoil was expected to use basically the same techniques as had been previously established for isothermal rolling of compressor vanestock. The tooling would be of refractory metal; force feed would be used to achieve high reductions per pass and to promote lateral spreading front tension would be used to straighten the emerging airfoil; and an optical pyrometer sighting on the workpiece would provide a feedback signal for control of temperature. The additional requirements for blade airfoil roll forging are related to nonsteady state conditions inherent in a short workpiece and the change in cross section due to taper of the airfoil.

The preform for blade airfoil roll forging was the root forgings discussed in Section 3.6.1. In general the airfoil rough roll forge operation involved the following ten steps:

1. Graphite lubricant was applied to the preform and dies by spraying.
2. Dies were rotated to align the root pockets with an imaginary line between the centers of rotation of the dies.
3. The tip end of the preform was inserted into the feeder nozzle with the root enlargement aligned with the root pockets of the dies.
4. The dies were closed upon the root enlargement using minimum squeeze force.
5. The front tension device was attached to the root end of the preform that extended from the dies.

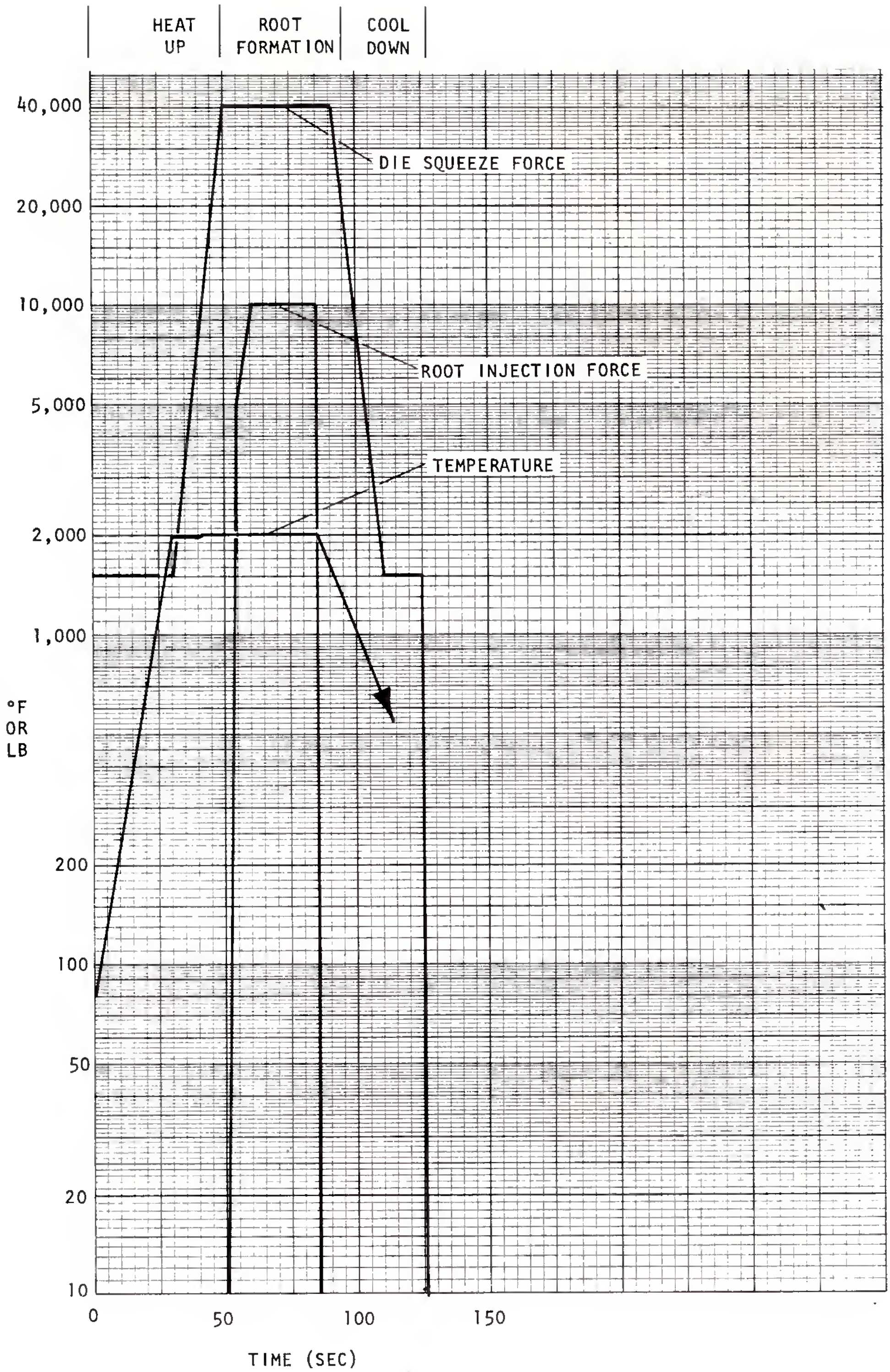



Figure 42. Parameter Profiles for Root Formation of T55 Second Stage Blade in AM-350 Alloy

Figure 43. Prototype Production Run of AM-350 Root Forgings (#77-3930)

Figure 44. AM-350 Root Forging From Production Run

6. Heating current was initiated and raised to temperature of the preform to the desired forging temperature as measured with an optical pyrometer sighting on the target marked $PYRO_{BLADE}$ in Figure 34.

7. Advanced the die squeeze force, maintaining constant temperature, until the upper platten was stopped against the mechanical stops. This squeeze force forges the root to within 0.020 inch of the finished thickness.

8. Applied feed force to the tip end of the blade, front tension to the root end and started the drive system to rotate the dies in the root to tip direction

9. At the end of the roll forge pass, the heating current was turned off, the tip feed force removed and the die squeeze force returned to minimum, maintaining the front tension for a few seconds until the blade cooled to below red heat.

10. Released the front tension, opened the dies and unloaded the roll forged blade.

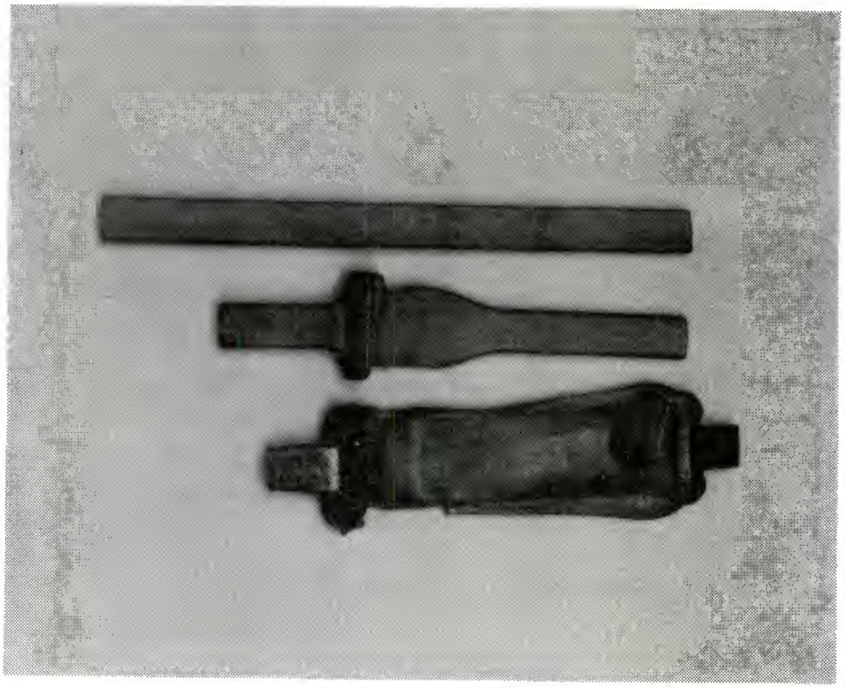
The total elapsed time for all ten steps was about 200 seconds.

The establishment of the process for rough roll forging involved the following parameters:

- Forging temperature and rate of temperature rise
- The rate of application of die squeeze force
- Magnitude of tip feed force
- Magnitude of front tension force
- Die gap

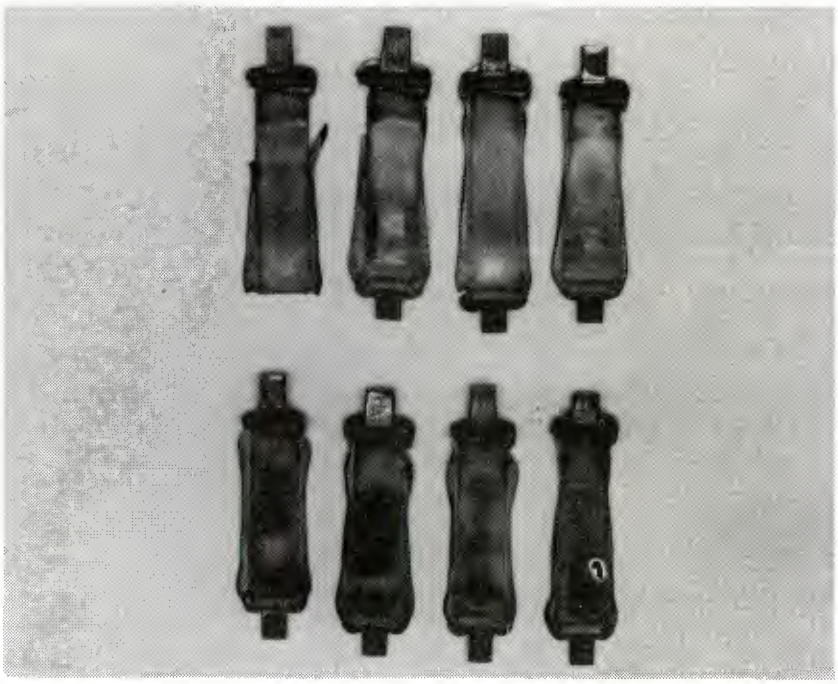
The magnitude of die squeeze force and roll forge speed were maintained constant at 40,000 pounds and 1.2 in/min. The function of the die squeeze force was to move the upper platten downward solidly against the mechanical stops and to thus fix the gap between the dies. Any constant force above about 30,000 pounds could have been used. This method of die gap control is not entirely satisfactory because elastic and thermal strains can creep into the process and affect the thickness of the forged blade. The roll forging speed of 1.2 in/min is very conservative and was selected to minimize risk of die damage during the establishment of the other parameters. Speed is generally the last parameter to be optimized. Roll forge speeds of 2 to 3 in/min should be achieved in Phase II.

The first airfoil roll forging trials were performed on Ti6Al4V alloy. Figure 45 shows titanium alloy blades that were roll forged in a single pass at 1700°F. Figure 45A shows a two-step process from feedstock to root forging to finished forged blade. By modification of the feeder systems, as discussed in Section 3.6.1, the blade could be made in a single step. The



A.

Preform, Root Forging, Roll Forged Airfoil



B.

Single Pass Roll Forged Blades

Figure 45. Ti6Al4V Blades Forged in Two Operations

only problem encountered with the airfoil roll forging was control of straightness. The titanium alloys are weak at the forging temperature and there was a tendency for the flash along the edges of the airfoil to momentarily adhere at localized points to the flashlands of the dies and thus were pulled off of the blade axis as the rotating dies move apart. It is believed that additional work on such items as flashland design, lubricants, front tension control and mechanical die strippers could resolve this minor problem.

The first series of roll forged AM-350 blades are shown in Figure 46

The roll forge parameters used and the dimensional results obtained are summarized in Table 6. Measurements were made of the maximum thickness at each of six airfoil stations (see Section 3.9) which are spaced at designated internals along the blade.

One objective of Phase I was to prove process reproducibility by demonstration of repetitive dimensional control of the forged blades.

A goal was to produce a series of blades that deviated less than 0.010 inch from the drawing tolerance. The results shown in Table 6 are remarkably good considering the small number of blades processed and the numerous parameter changes that were made. For example, the first blade specimen rolled with new dies and machine set-up was in the tolerance band except at Station G where it was thick by 0.001 inch. This blade specimen is shown in Figure 47. All the specimens were roll forged at constant temperature, rolling speed, and atmopshere. The variables examined were preform shape, lubricant, squeeze force, die gap, feed force and front tension. An analysis of the results of this first series of blades is presented next.

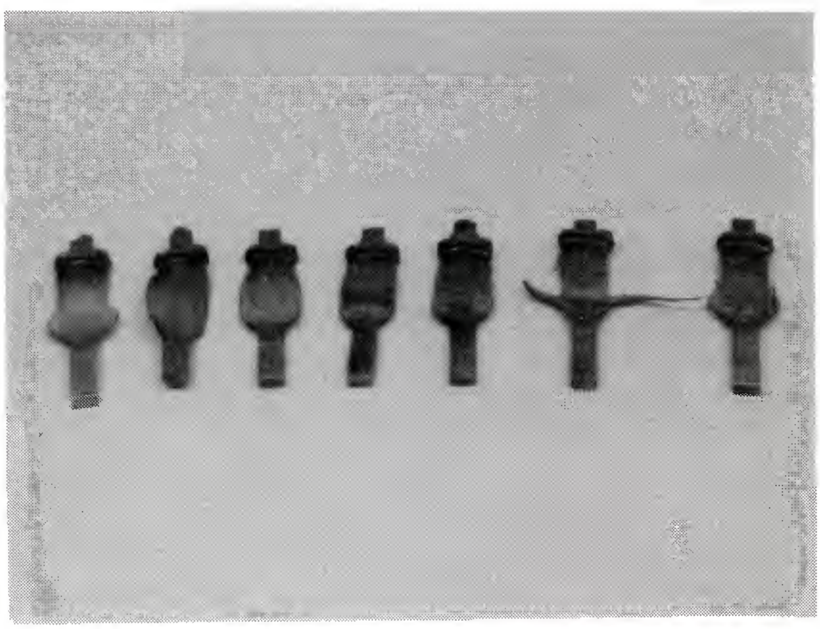


Figure 46. First Isothermal Roll Forged Blades in AM-350 Alloy

Table 6

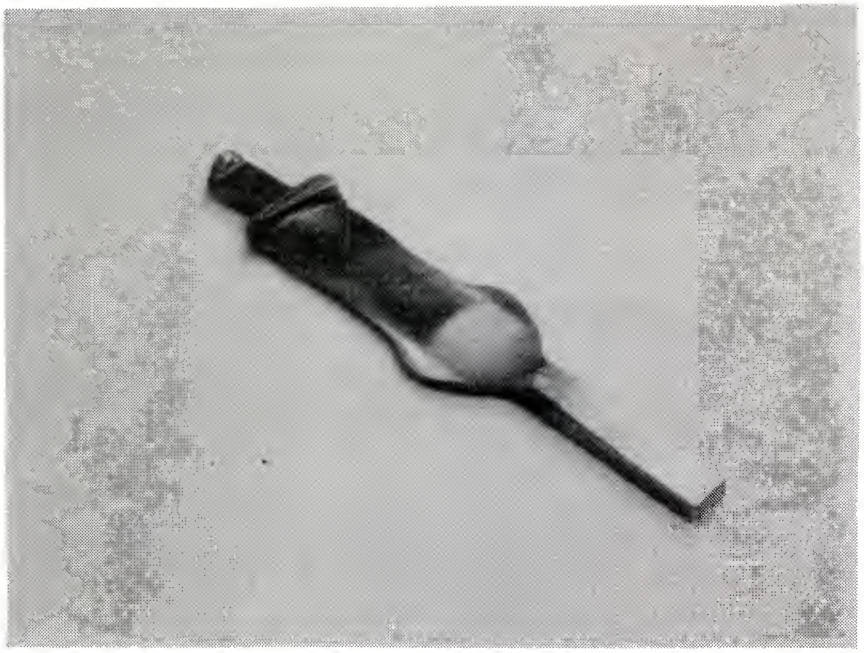
Dimensions and Roll Forge Parameters for First-Off AM-350 Blades*

| Blade Specimen | Thickness Deviation From Tolerance Band ($10^{-3}$ inch) Airfoil Stations | | | | | | Roll Forge Parameters[1] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Root N | L | J | G | E | C Tip | Preform Shape | Lubricant | Squeeze Force (lbs) | Die Gap Adjustment (inch) | Feed Force (lbs) | Front Tension (lbs) |
| 1 | ● | ● | ● | +1 | ● | ● | Straight | #204[4] | 30,000 | 0.000 | 1200 | 60 |
| 2 | +4 | ● | ● | ● | ● | +4 | Tapered[2] | | | | | |
| 3 | ● | ● | +2 | +1 | +1 | +5 | | | | | 600 | |
| 4 | ● | ● | ● | +8 | +16 | +26 | | | | | | 120 |
| 5 | ● | ● | +5 | +1 | +1 | +9 | | Dylon[3] | | | | |
| 6 | ● | -5 | -5 | -2 | ● | ● | Straight | | 40,000 | -0.007 | 1200 | |
| 7 | -4 | ● | ● | ● | ● | +11 | | | | -0.002 | | |
| 8 | -1 | -3 | -2 | ● | ● | ● | | | | | | |
| 9 | ● | -2 | ● | ● | ● | ● | | | | | | |

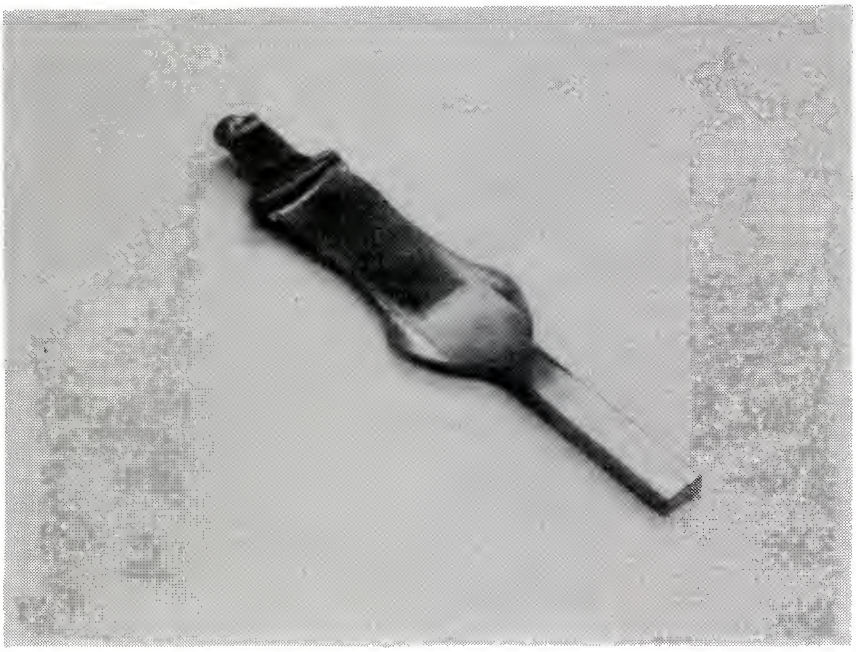
● Within tolerance band allowed for Phase I consisting of ±0.002 inch from nominal, plus an additional 0.010 inch on high side.

*Produced by one pass roll forging.

1. Constant: Forging temperature 1950°F (optical); rolling speed 1/2 in./min; argon atmosphere.
2. Tapered to reduce die overfill at blade tip.
3. Dylon Grade AE diluted 1:1 with water and sprayed onto preform heated to approximately 400°F.
4. Sprayon Dry Graphite #204 - Solids: Atchison colloidal graphite DAG-143. Cutting Solvents: (1) isopropyl alcohol; (2) methyl chloride. Propellant: 50% propane - 50% isobutane.



Suction Side



Pressure Side

Figure 47. Compressor Blade Isothermal Roll Forged From AM-350 Alloy in One Pass; As Forged Condition

The system stabilized during the first five blades and gave indication the die gap was too large. A squeeze force increase and die gap decrease overcorrected and resulted in thin blades. A further gap adjustment brought Blade Nos. 7, 8 and 9 close to the desired thickness. The overthickness condition near the blade tip was caused by premature stopping of the rolling pass and the underthickness condition near the root was a carryover of a thin condition in the preform resulting from the prior root forging operation. Both conditions are considered readily correctable. Of all the variables, squeeze force had the greatest influence on blade thickness. Preform shape had little effect, however this variable is important in control of flash and probably the rate of wear of the flashlands of the dies. The advantage of one graphite base die lubricant over the other was not established by these few tests. The Dylon lubricant may have an advantage in that it can be applied more readily to hot dies. The parameters of feed force and front tension are of secondary importance to thickness control and relate primarily to control of chord and straightness. This blade roll forging session demonstrated the effectiveness of the atmosphere enclosure in preventing burn-up of the lubricant and oxidation of the dies and workpiece.

From the results of the first series of roll forged AM-350 blades it was decided that the airfoil thickness probably could be controlled to closer tolerances with the existing roll forge machine if two, rather than just one, roll forge passes were used with a flash trim between passes. The first question was how much material should be left for the finish pass. The amount left should be small to minimize metal flow in the final pass, however there must be enough left to provide sufficient area of contact with the dies so that the current required to heat the blade also will be adequate to heat the dies. Calculation indicated that a final reduction of 0.020 inch should provide adequate die contact area. The mechanical gap stops were adjusted 0.020 inch and a series of 20 AM-350 blades were rough roll forged. The parameter profiles selected from this series are shown in Figure 48. The selected parameters were:

40,000 pound die squeeze force

1900°F setpoint temperature

1680 pounds tip feed force

190 pounds front tension

1.2 in/min rolling speed

graphite lubricant (Spray On No. 204)

argon atmosphere

The rough forged blades produced by this schedule were fully formed with minimal flash, were overthickness on the average by 0.022 inch with a standard deviation in thickness of 0.0049 inch.

Treating the root formation and rough airfoil roll forge steps as separate operations the total processing time in the forging machine was 325 seconds. Through modification of the feeder system, it should be possible to combine the two operations and reduce the total time to under 250 seconds as shown in Figure 49.

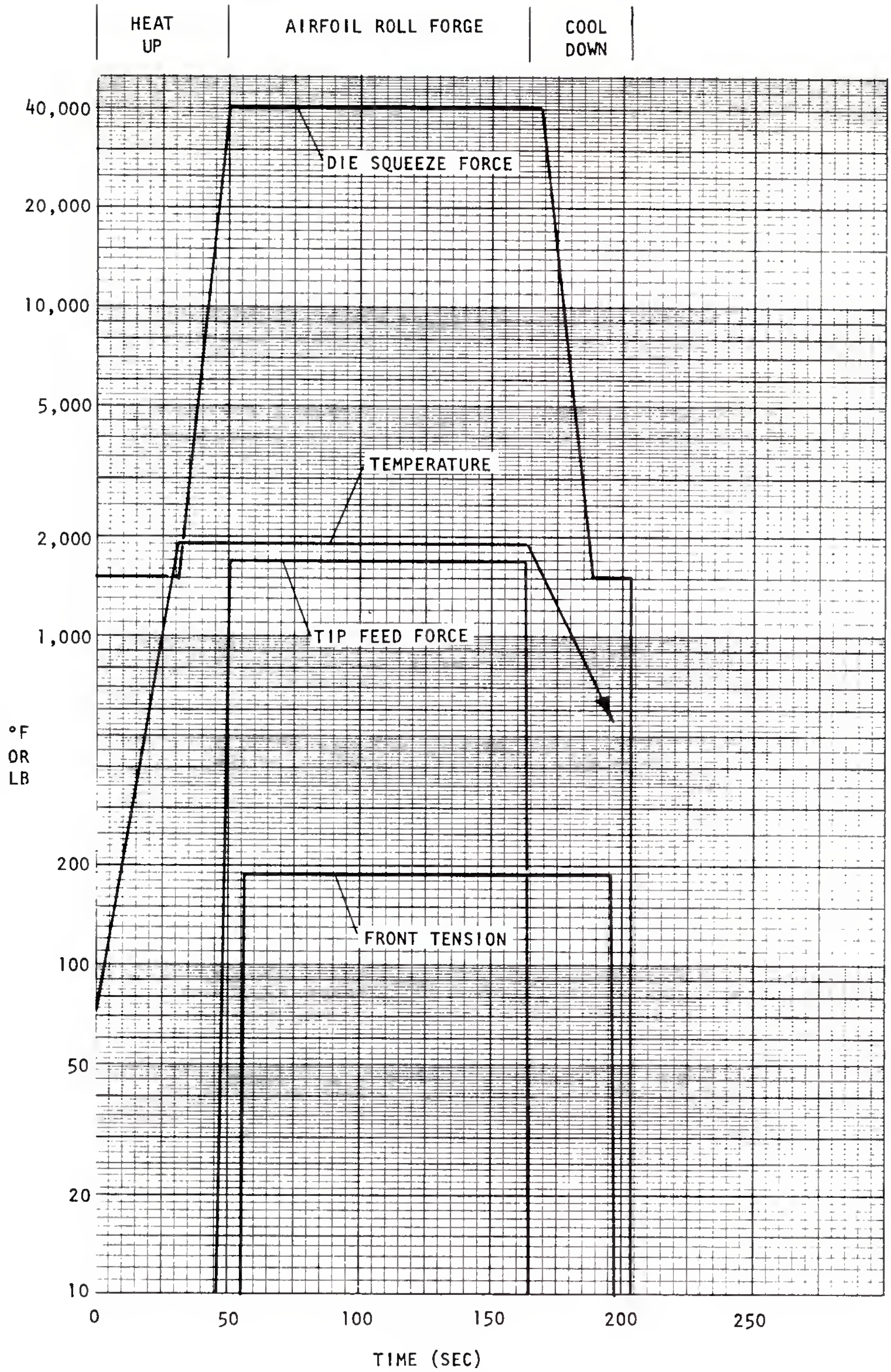



Figure 48. Parameter Profiles for Airfoil Roll Forging of T55 2nd Stage Blade in AM-350 Alloy

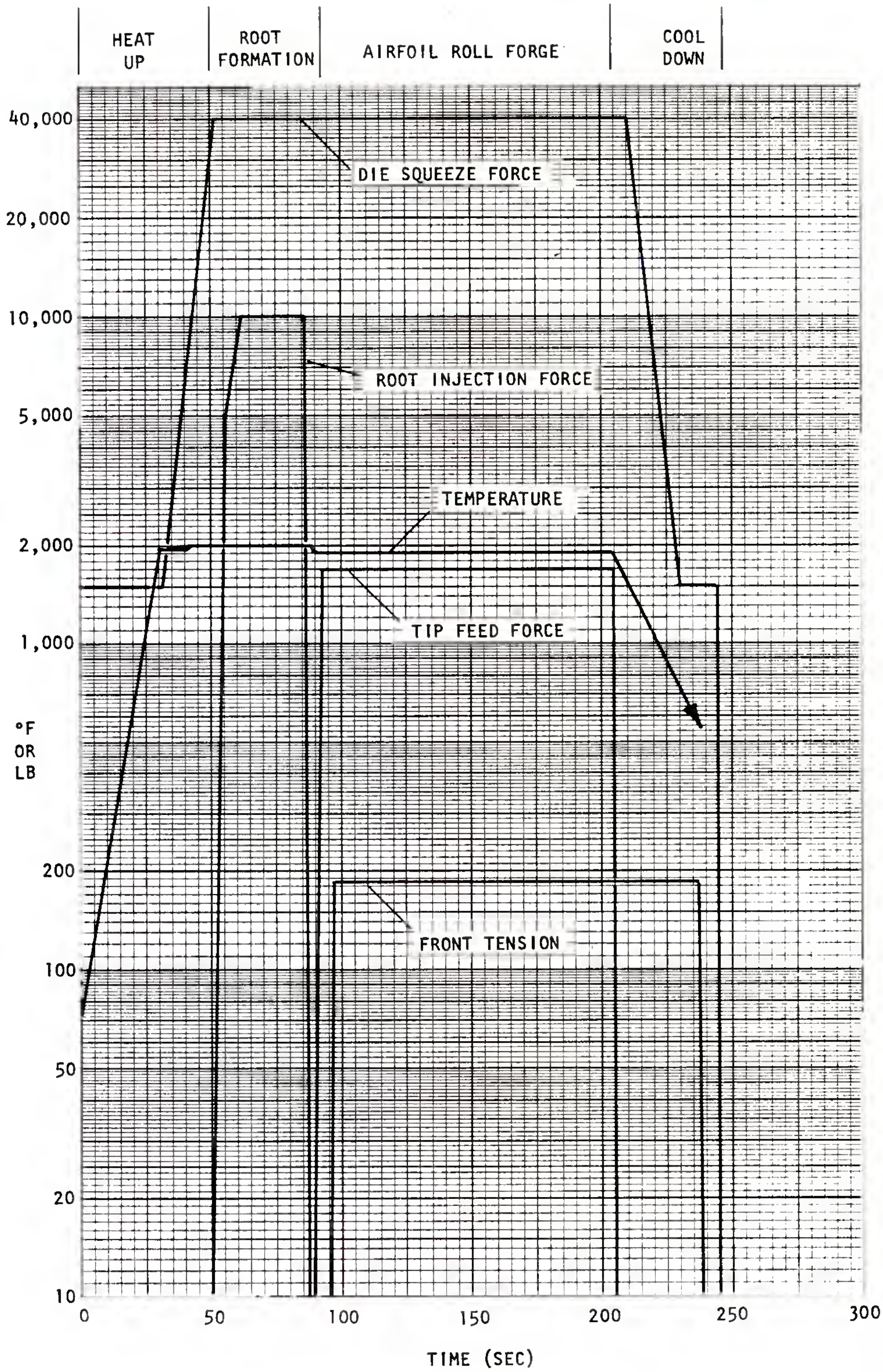



Figure 49. Parameter Profiles for Root Formation and Airfoil Roll Forging of T55 2nd Stage Blade in AM-350 Alloy

### 3.7 TASK 7 - FINISH ROLL FORGING

The selected process for finish blade forging (see Fig. 10) consists of press forging of the root followed in the same operation by a finish roll forge pass of the airfoil moving from root to blade tip. The preform for this operation was produced from the rough roll forging described in Section 3.6.2, where approximately 0.010 inch per surface was left for the finish forging operation. The preform was prepared for the finish forging operation by bandsawing of the flash, belt sanding the saw cut edges to remove burrs and sand blasting to prepare the surface for the graphite lubricant. The die gap was adjusted for finish forging by removing 0.020 inch from the mechanical stops. The blades shown in Figure 50, were finish roll forged using a process consisting of the following steps:

1. Graphite lubricant was applied to the preform and dies by spraying.

2. The dies were rotated to align the root pockets with an imaginary line between the centers of rotation of the dies.

3. The preform was placed upon the lower die with the root aligned with the die root pocket.

4. The dies were closed upon the root enlargement using minimum squeeze force.

5. The front tension device was attached to the root end of the preform which extended from the dies.

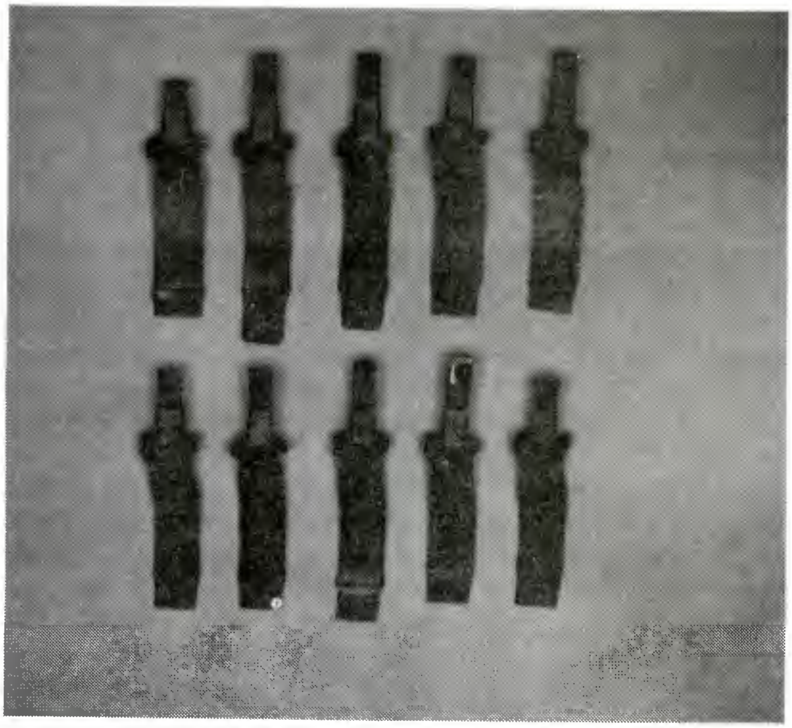
6. Heating current was initiated and advanced to 6200 amperes.

7. The die squeeze force was to 40,000 pounds and the heating current was simultaneously advanced to 13,500 amperes so as to maintain nearly constant temperature as the upper platten is stopped against the mechanical stops. This squeezes the root to finish thickness.

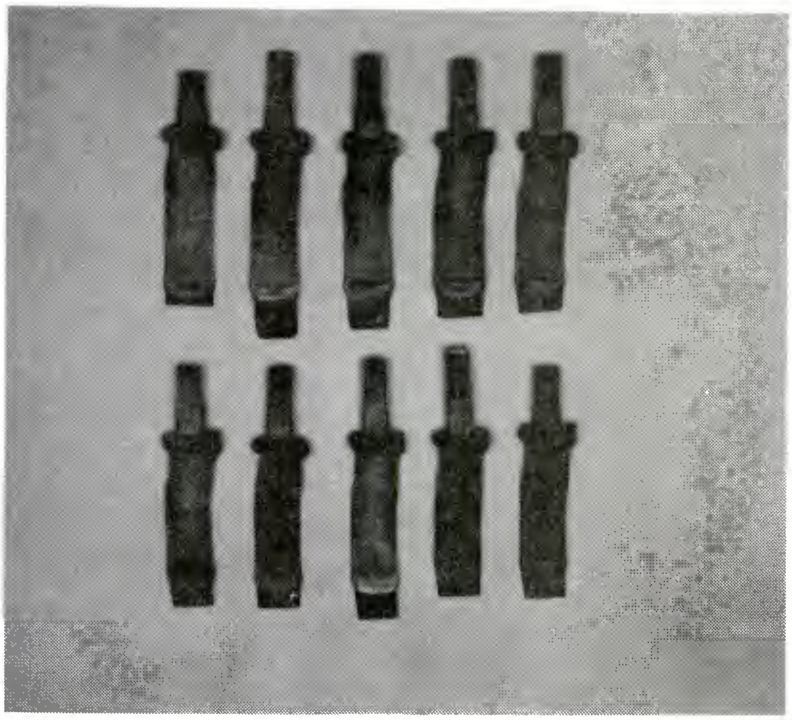
8. Front tension was applied and the drive system started to rotate the dies in the direction from root to blade tip. Gradually reduced the heating current from 13,500 to 11,800 amperes to maintain nearly constant temperature and simultaneously decreased the front tension so as to maintain nearly constant tensile stress in the tapered airfoil.

9. At the end of the roll forge pass, the heating current was turned off and the die squeeze force returned to minimum, maintaining the front tension for a few seconds until the blade cools below red heat.

10. The front tension was released, the dies opened and the finish forged blade was removed from the dies.



A. Suction Side



B. Pressure Side

Figure 50. Compressor Blades Isothermal Roll Forged in AM-350 Alloy Using Two Roll Forge Passes; as Forged Condition

The total elapsed time for this sequence of steps was about 250 seconds. This finish roll forge operation is very similar to the rough roll force sequence described in Section 3.6.2, except for the following important differences:

- Process temperature control by feedback from an optical pyrometer could not be used during finish roll forging because of the poor optical access to the blade due to the decreased gap between the dies. A program for current was established based on pyrometry of the die surface, supplemented by operator judgment of the relative temperature difference between the dies and the workpiece.

- Feed force was not required to accomplish the 0.020 inch reduction of the finish roll forge pass.

- Lateral constraint of the preform as it entered the rolling dies was found necessary to prevent skewing of the preform and incomplete filling of the trailing edge of the airfoil. This defect can be seen in all of the blades in Figure 50 except for the one at the lower right where lateral constraint was used.

The selected process for finish roll forging is shown in Figure 51. An AM-350 compressor blade being finish roll forged is shown in Figure 52. The blade is being withdrawn root first toward the left. The evaluation of the finish roll forged blades is presented in Section 3.9.

While finish roll forging the above series of ten AM-350 blades the primary control loop was current. Simultaneously, measurements of voltage drop were made from die to die through the workpiece. The results of these measurements are plotted in Figure 53. During the roll pass the die voltage decreased slightly while the die to workpiece contact area was being established, then the voltage increased gradually as rolling progressed, accelerating abruptly near the end of the run. A plot of the product of current and voltage shows that the power dissipated increased about 30 percent as the current was decreased some 11 percent. The very large voltage variation observed which was repetitive from blade to blade, suggests the parameter of power may provide a reliable means of temperature control when optical access is unavailable. It is planned to pursue this approach in Phase II.

## 3.8 TASK 8 - FINAL OPERATIONS

Final operations in the manufacturing process were planned to include edge finishing and heat treatment.

Heat treatments were investigated at both Avco and Solar. Work at Avco, reported in Section 3.5, showed that isothermally rolled AM-350 would respond satisfactorily to all standard heat treatments. This was encouraging because

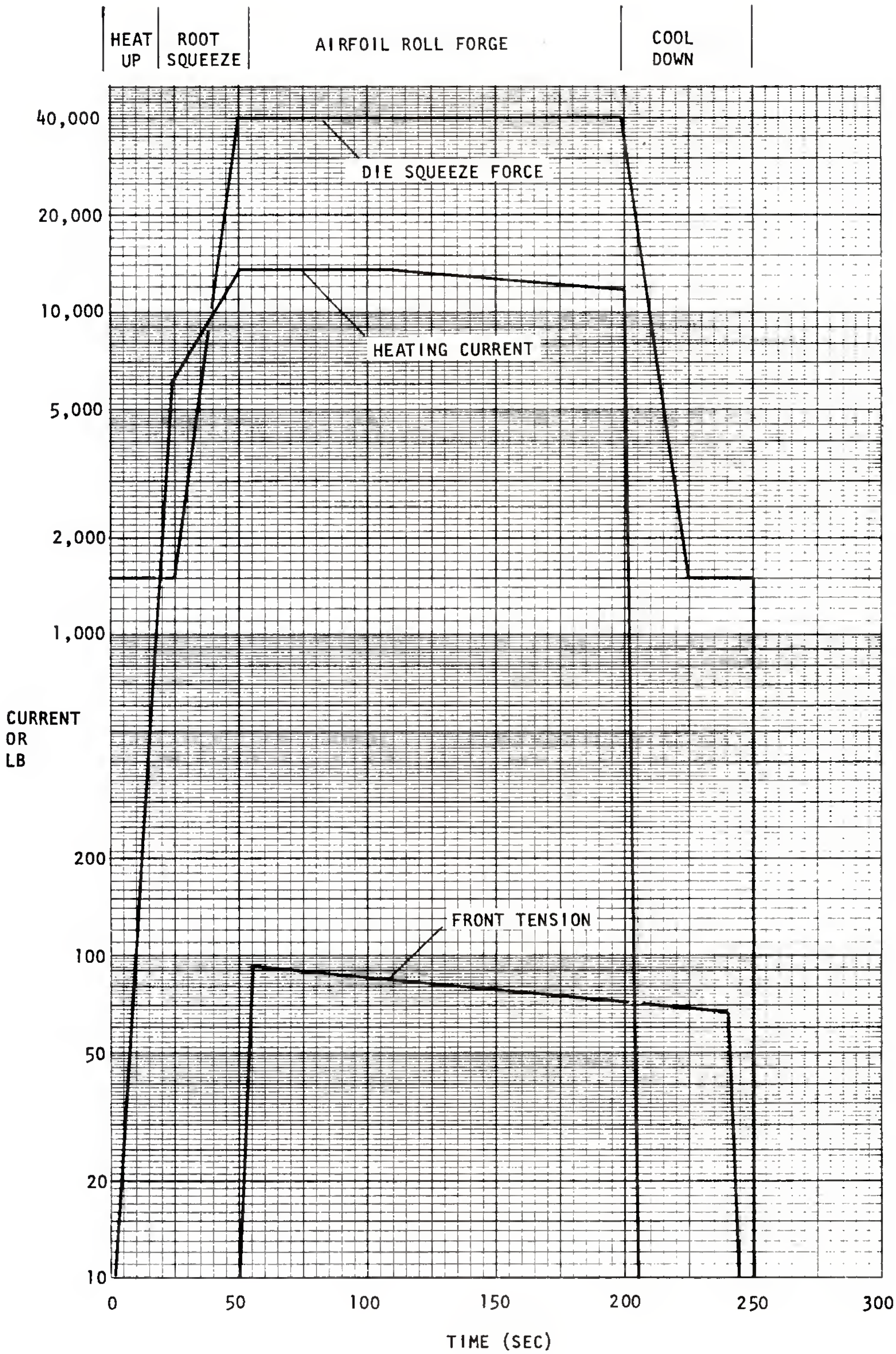



Figure 51. Parameter Profiles for Finish Roll Forging of T55 Second Stage Blade in AM-350 Alloy

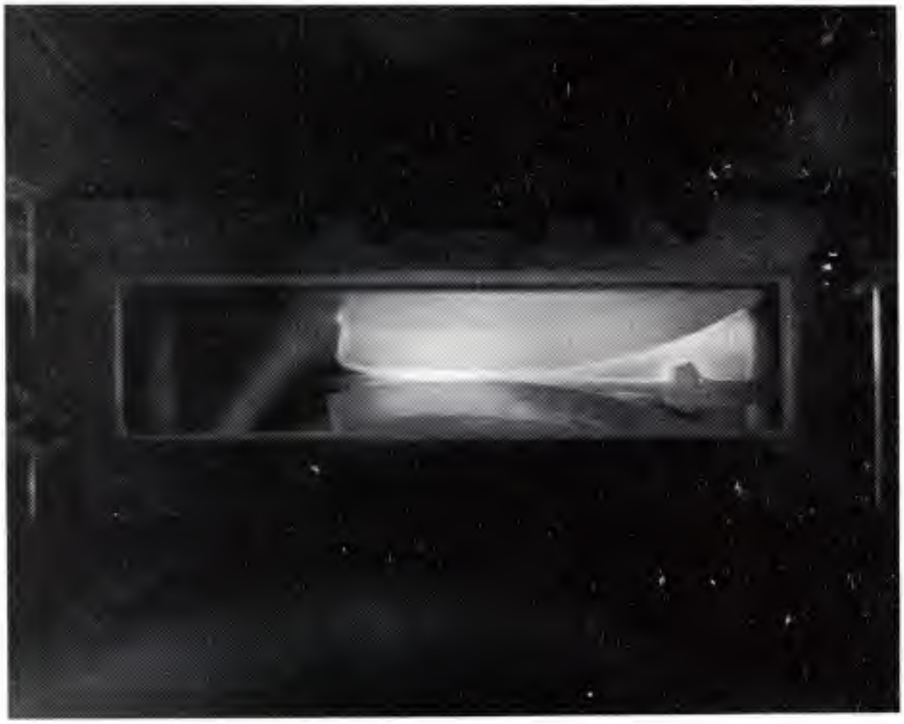


Figure 52. Finish Roll Forging of T55 Blade in AM-350 Alloy (#77-4527)

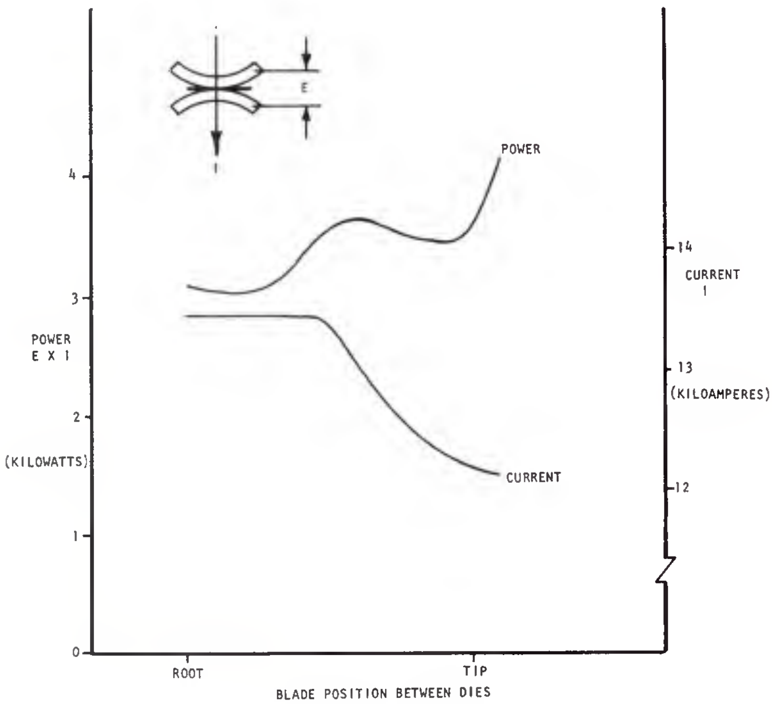



Figure 53.

Electric Power and Current Measurement Made While Finish Roll Forging AM-350 Blade

of the increased freedom indicated for the total process. These results were confirmed in preliminary work at Solar although this work was restricted to response in microstructure.

Edge finishing is the second of the final operations under study on this program. As pointed out earlier, it is believed to be a critical operation in terms of costs where isothermal roll forged blades will require less finishing. Further, it is expected that the preservation of airfoil contour almost to the flash line, coupled with the thinner flash, will eliminate hand finishing and permit automatic operations to be used. In order to examine this approach, some lengths of isothermally rolled airfoil were available from other work at no cost to the program. Advantage was taken of this opportunity to establish finishing methods.

Figure 54 presents a comparison of the typical conditions at cold rolled and isothermally rolled leading or trailing edges. In contrast to the departure from contour of the cold rolled airfoil, the isothermal rolled section maintains contour almost to the flash. Airfoil station profiles of blades will be presented in the next section to confirm this point. The possibility of automatic finishing the isothermal rolled airfoil versus the need to remove significant metal by hand finishing is readily appreciated.

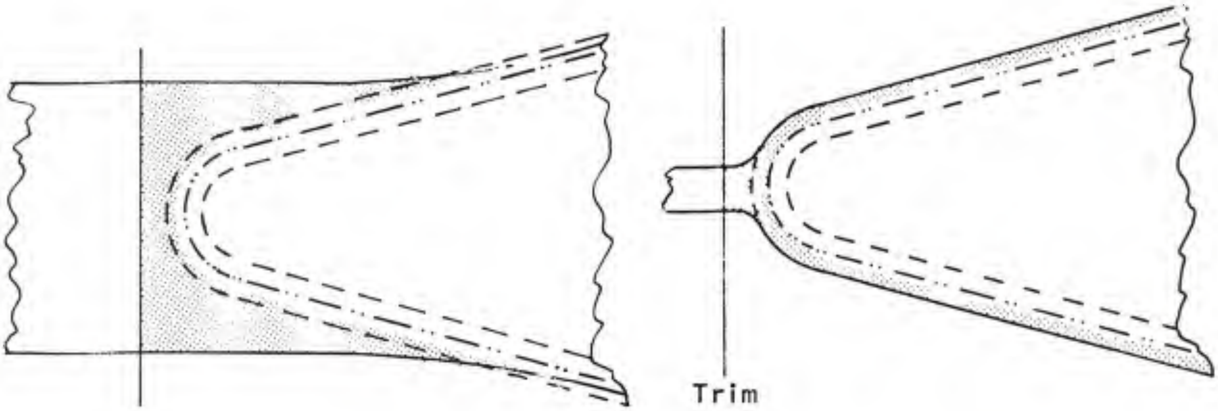
The available isothermally rolled airfoil is shown in Figure 55A. It can be seen that the flash matches the ideal condition shown in Figure 54. Figure 55B shows the same section after 15 hours in a small Sweco finishing mill.

## 3.9 TASK 9 - EVALUATION

Evaluation of blades was conducted at both Solar and Avco. The principal evaluations at Solar were: preliminary metallurgical evaluation; dimensional analysis; and a preliminary cost analysis. Owing to the delay in selection of the manufacturing process as a result of the reversal of operational sequences, the Avco evaluation is continuing and will be reported separately.

### 3.9.1 Metallurgical Evaluation

Metallurgical evaluation of isothermally rolled AM-350 strip was reported in Section 3.5 together with heat treatment studies and mechanical property tests conducted by Avco. This work was performed on material supplied by the Utica Division of Kelsey-Hayes and was the same batch used by Utica for a production run of T55 2nd stage blades by the cold roll process.




Typical Cold Rolled

Isothermal Rolled

Figure 54. Airfoil Edge Finishing Requirements

A. "As-Rolled" Airfoil
Magnification: 3.5X

B. After Sweco Finishing
Magnification: 3.5X

Figure 55. Automated Finishing of Isothermally Rolled Airfoil

Preliminary work was performed on a different batch of material to conserve the material meeting the Avco specification. However, it was felt adequate to study many aspects of the metallurgy that occur in the isothermal roll forging process, including tool proofing.

Figure 56 shows the microstructure of the AM-350. Subsequently, Avco indicated that the structure is marginally acceptable and is not equal to the quality of the material supplied by Utica, although the composition and mechanical properties were certified to meet specification AMS5734A by the vendor. Differences between this and the material meeting the Avco specification are small and relate to grain size, distribution of carbides and delta ferrite. Noteworthy here are the somewhat massive but almost continuous stringers of delta ferrite in the longitudinal direction.

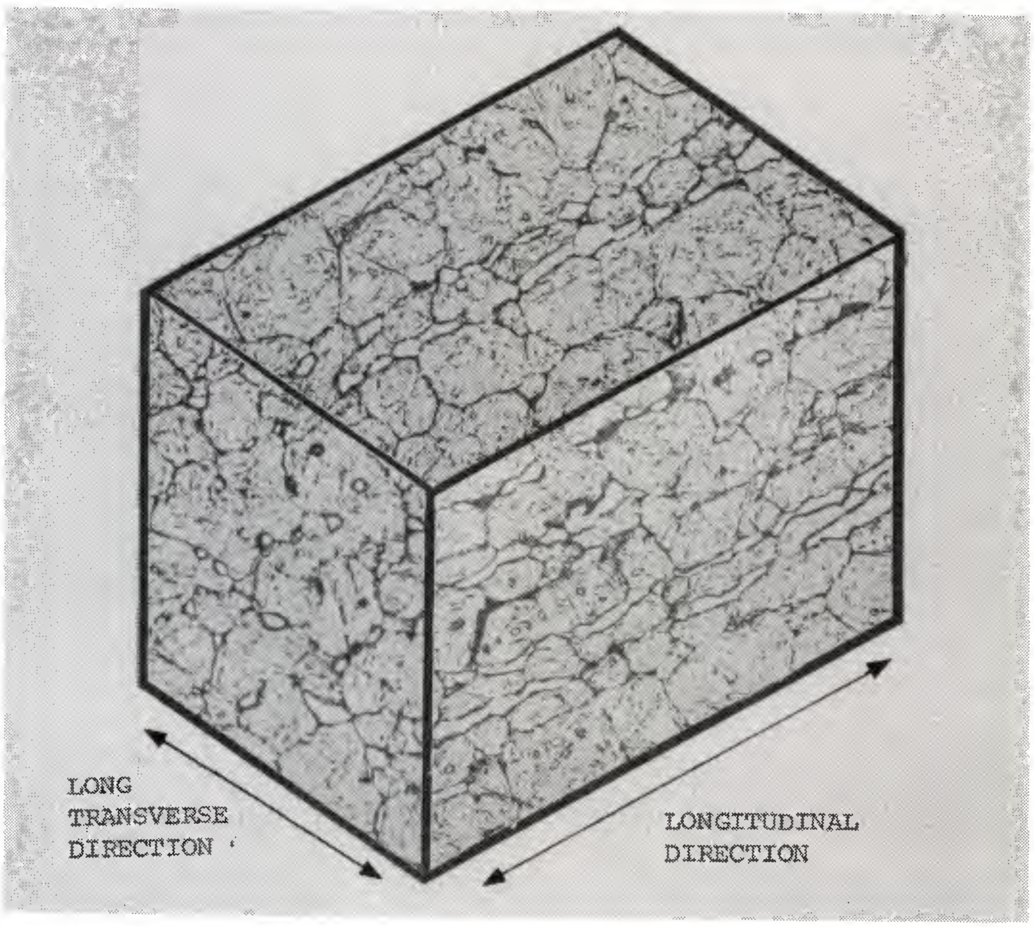



Figure 56. Micrographs of Three Primary Directions of AM-350 Feedstock in Heat Treated Condition. Marble's Etchant - Magnification: 500X

Figure 57 shows a longitudinal section through a root forging made by the feedstock injection method. The sections have been given the Avco-recommended heat treatment. These sections may be compared with the longitudinal section in Figure 56. It can be seen that the marked delta ferrite stringers have been broken up by the combination of upsetting and lateral flow in the root section, but remain visible in the airfoil sections.

Figure 58 shows the same sections from Figure 57 after 20 seconds of etching. These show the martensite in the austenite grains. Closer examination shows that the deformation in the airfoil has removed the continuity of the delta ferrite stringers but the ferrite grains remain lined up in the longitudinal direction. Refinement of the austenite grain size can be seen.

In addition to structural effects of roll forging, the examination included surface effects. Figure 59 shows the root platform. It has good smoothness as forged, but does give indications of heavier etching grain boundaries that are associated with some grain boundary diffusion inward of carbon from the lubricant. The depth of affected material is approximately 0.001 inch, and much of this penetration will have occurred in the solution treatment cycle of the heat treatment. Figure 60 shows conditions on the pressure side of the airfoil. More marked diffusion is noted. The solutions to this problem were recognized to be:

- A faster forging cycle
- Lower forging temperature
- Better clean-up before heat treatment.

All three methods were used to solve the problem. As experience was gained, the forging temperature was attained more rapidly and injection was accomplished in 15 seconds instead of the the 45 seconds used here. Next, the forging temperature was reduced, partly for other reasons from the 2100°F used in these tool proof samples to a temperature of 2000°F.

Figures 61, 62 and 63 show the effect of reducing the forge cycle from 45 to 15 seconds. There appears to be less complete breakup of the ferrite stringers under these conditions, but the surface is free of carbide penetration except in one localized area of the transition radius as shown in Figure 63. This attack occurred at the point of initial die contact where overtemperature resulted when the heating cycle was started. This overtemperature also caused some loss of die contour as indicated by the sharpening of the radius in Figure 63. Both this problem, and the resulting carbon penetration were solved by contouring the feedstock as shown in Figure 32 to fit the die contour at the position of initial contact, thus avoiding points of high current density and overheating when the heating current is initiated.

### 3.9.2 Dimensional Analysis

Ten blades were roll forged in the final sequence to check out the process selection. These blades were in the series 8/22/1 through 8/23/7. The

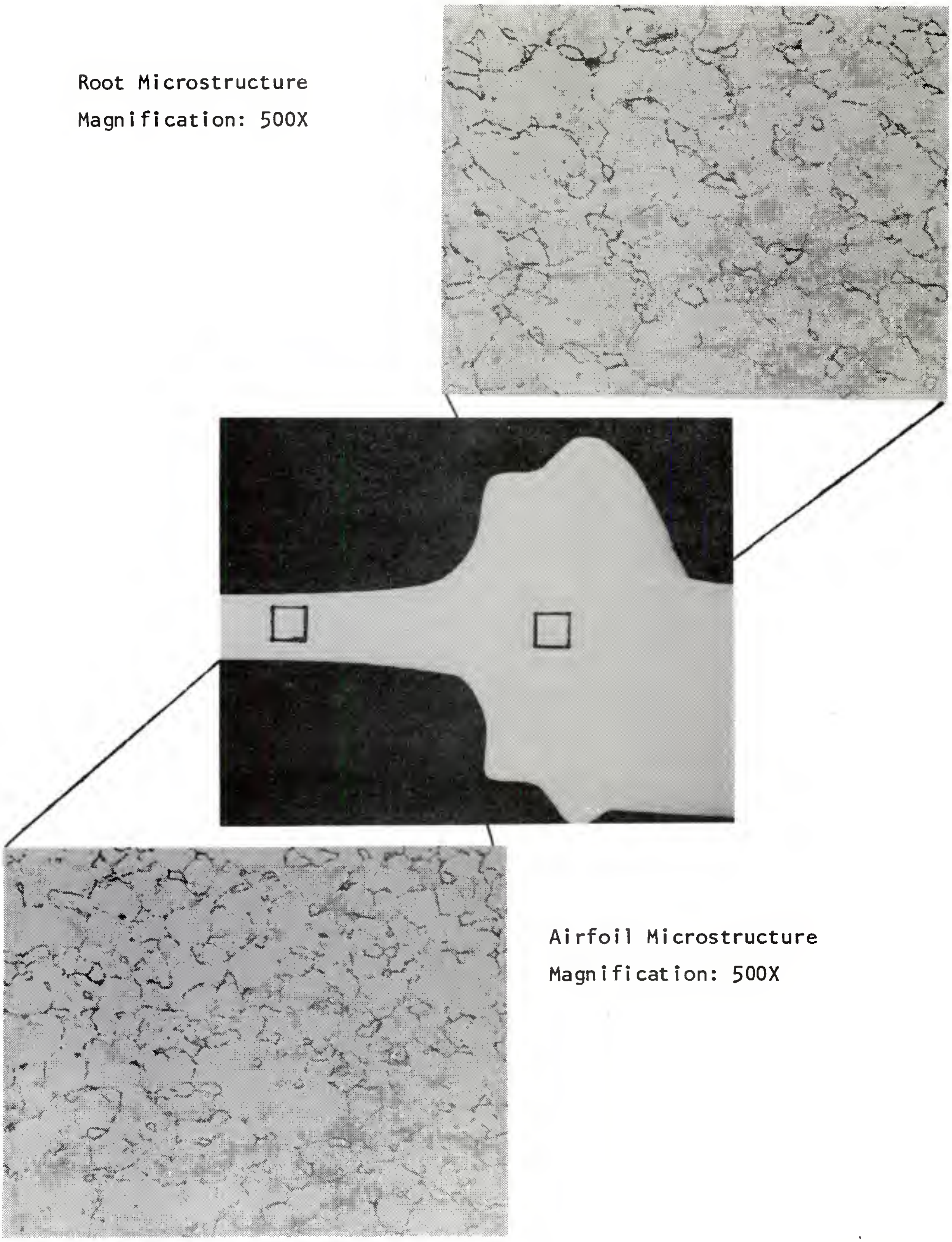
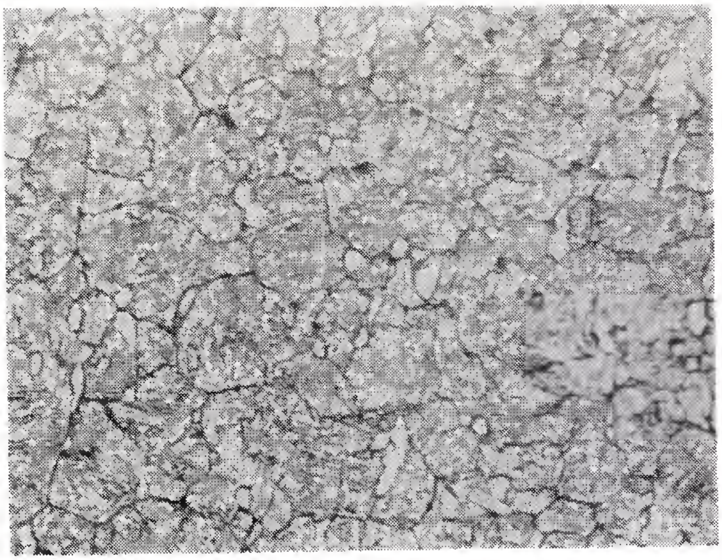
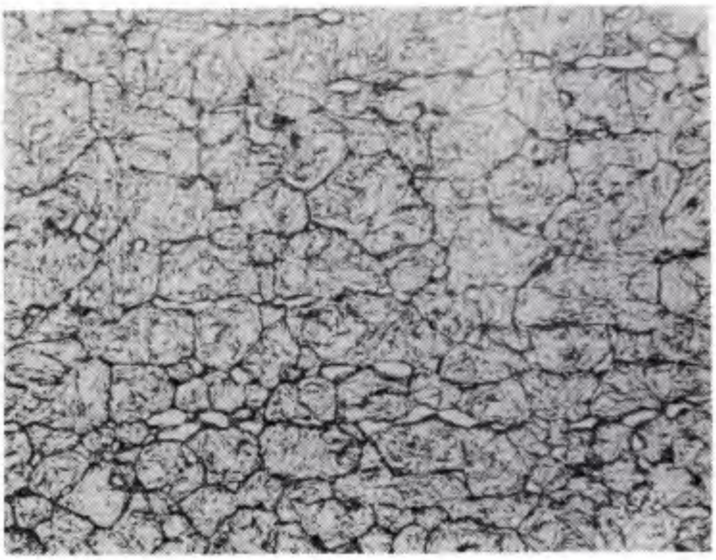



Figure 57. Section Through Blade Stacking Axis Showing Profile and Microstructure of Heat Treated AM-350 Root Forging. Marble's Etchant (10 sec)



A. Root



B. Airfoil

Figure 58. Microstructure of AM-350 Blade Forging.
Marble's Etchant - 20 Seconds.
Magnification: 500X

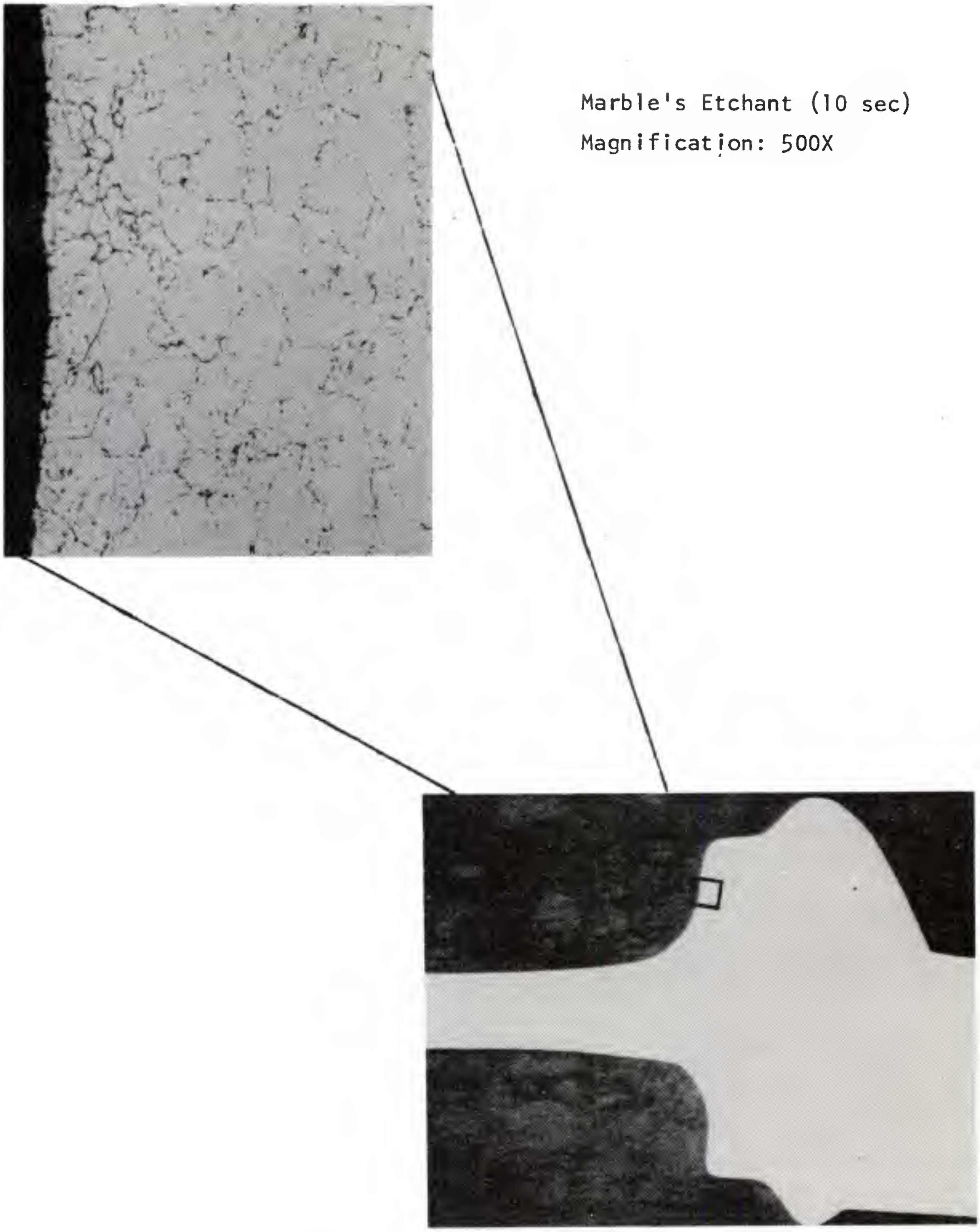
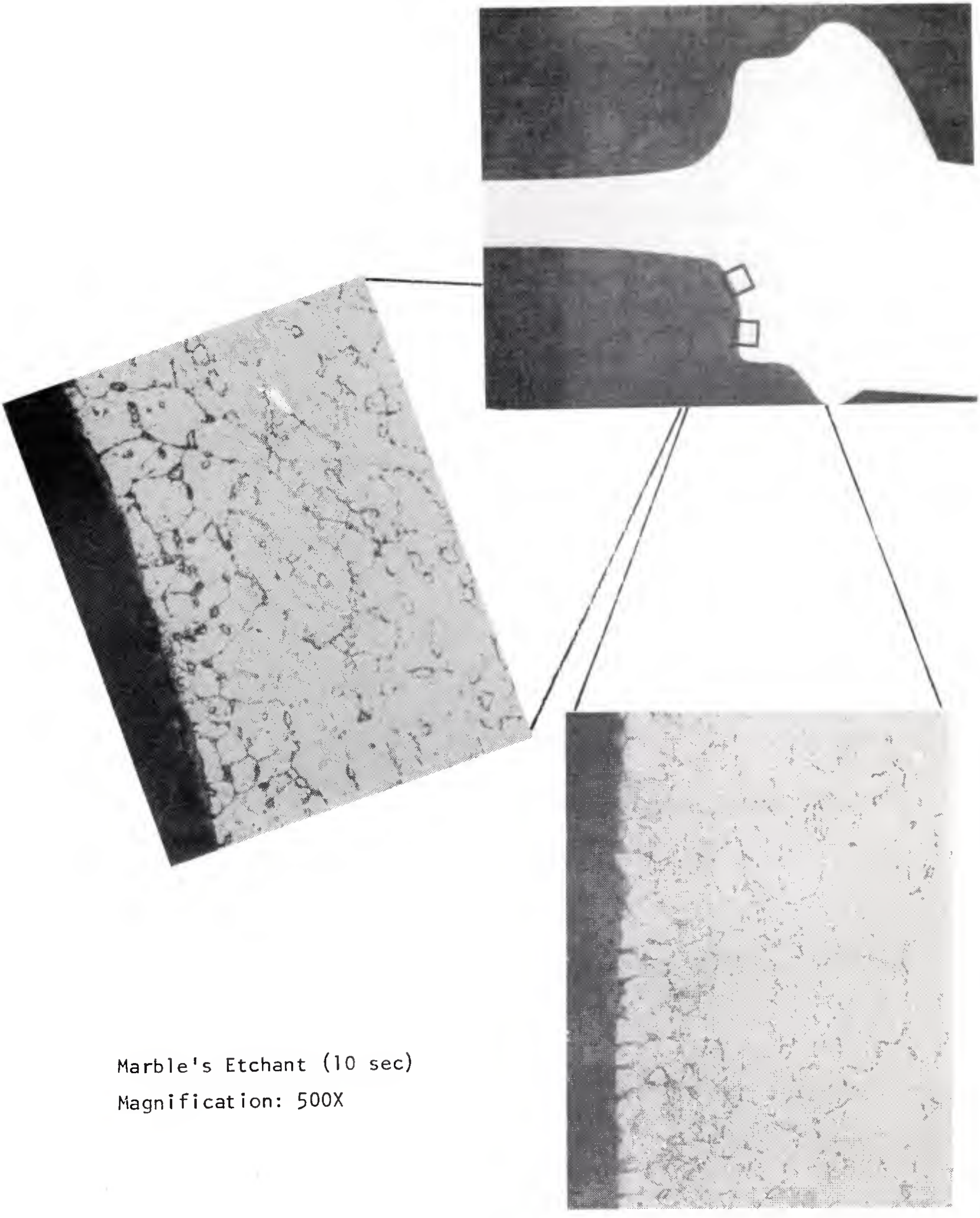


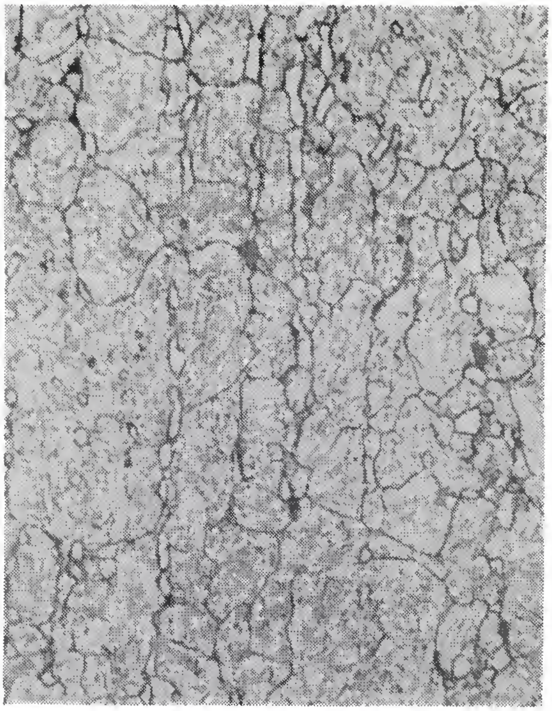

Figure 59. Microstructure of Root Platform on Suction Side of Airfoil of Heat Treated AM-350 Forging



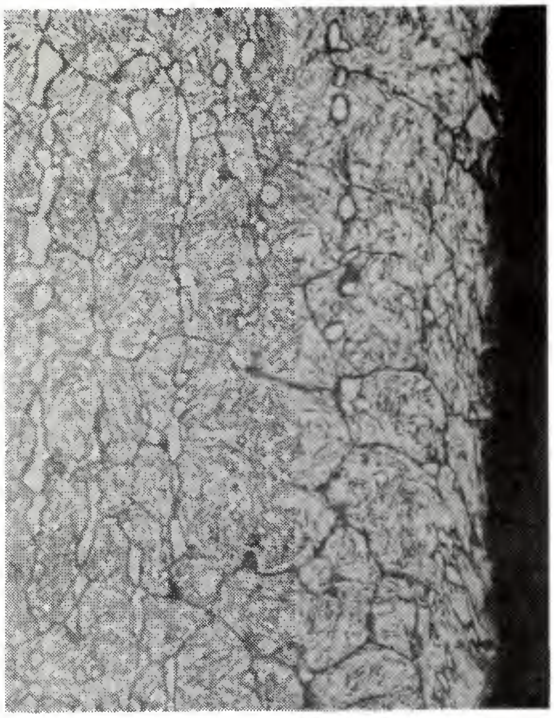
Marble's Etchant (10 sec)

Magnification: 500X

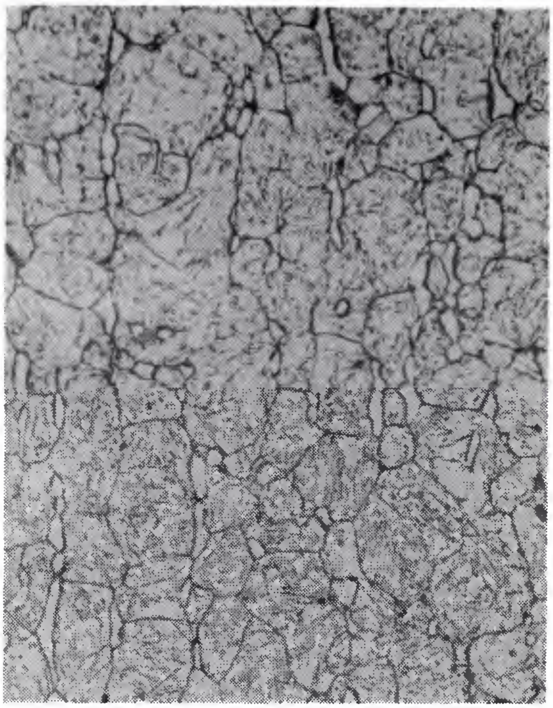
Figure 60. Microstructure of Transition Radius and Root Platform on Pressure Side of Airfoil of Heat Treated AM-350 Forging



Airfoil Centerline



Airfoil Surface

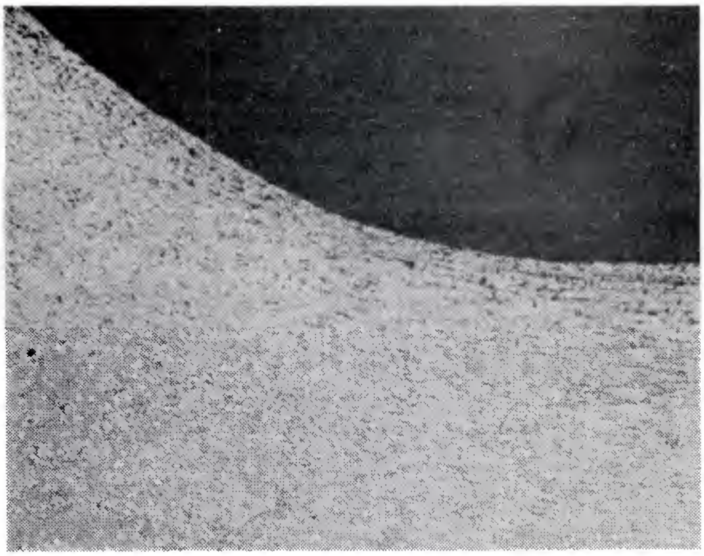


Root Centerline

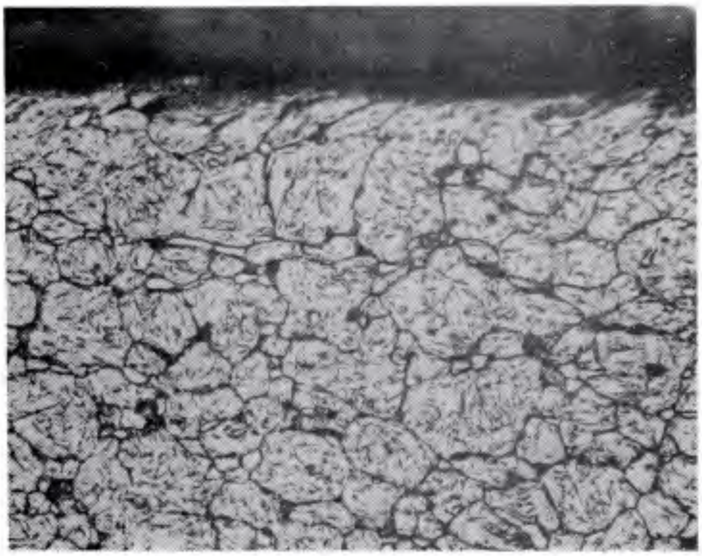
Figure 61.

Microstructure of Heat Treated AM-350 Root Forging

Root Forging Time: 15 Seconds
Marble's Etchant: 10 Seconds
Magnification: 500X

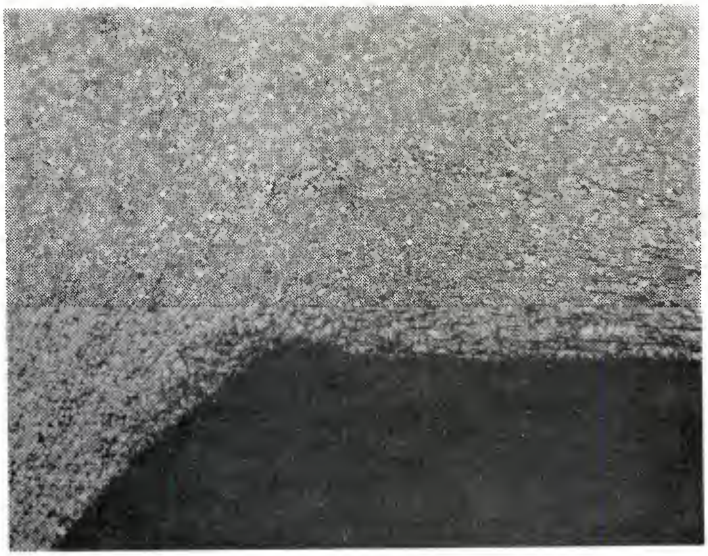


Magnification: 50X



Magnification: 500X

Figure 62. Microstructure of Transition Radius on Suction Side AM-350 Root Forging. Marble's Etchant: 10 Seconds



Magnification: 50X

Magnification: 500X

Figure 63. Microstructure of Transition Radius on Pressure Side of AM-350 Root . Forging. Marble's Etchant: 10 Seconds

principal dimensional analyses were: $t_{max}$ at the six stations N, L, J, G, E and C (see Fig. 64); profile traces at selected stations; and dimensional analysis of die position.

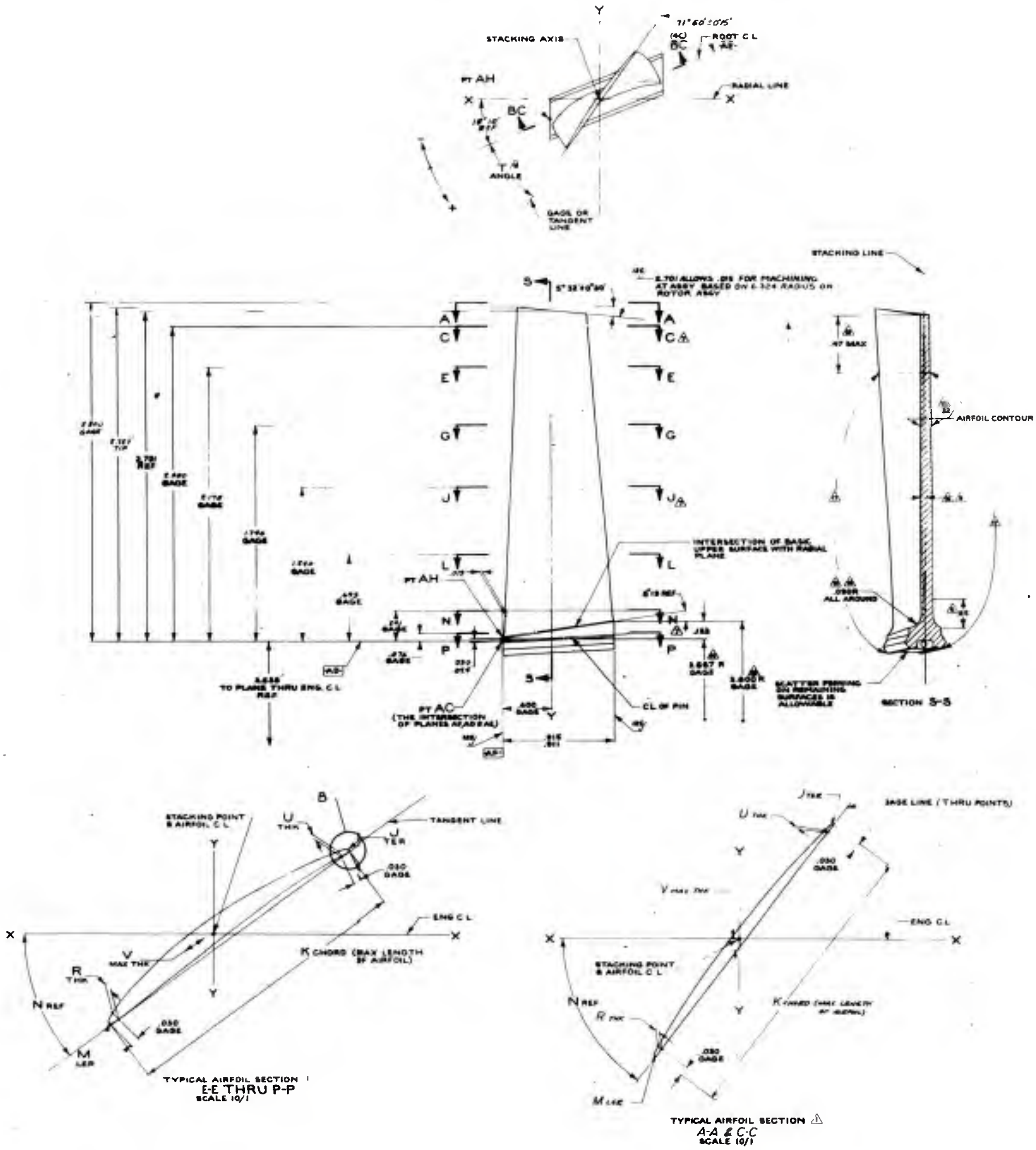
The $t_{max}$ values were determined by two methods. The first was ball point micrometer readings at the time of the forging sequence to guide the development of the forging process. The second was a Gage Room measurement with calibrated pin micrometers and precisely scribed station lines. Both sets of readings are reported because three of the blades were sent to Avco and were not available for the more accurate measurements. Typically the second set of measurements were within 0.001 inch of the first set made in the forging shop. In neither case was a clean-up performed so that the numbers represent as-forged surfaces.

The contour traces were made by Solar's inspection department using standard techniques used for compressor blade inspection. Figure 65 shows projection of airfoil contours of AM-350 blade 8-22-1.

The contours of airfoil stations L-L and J-J were made with a contour transcriber machine (Model 624) made by Optical Gaging Product, Inc. The projection contours replicated the actual blade contours within 0.0005 inch. Photographs comparing the projections with the 20X master profiles were made on the screen of a Jones and Lamson optical comparator (Model Epic 30). These tracings supplement the maximum thickness data presented in this section by showing the envelope of the airfoil is also in close conformance to the master profiles. The deviation at the leading edge is within tolerance with respect to the chord dimension (+0.005 in./-0.025 in.), however it is recognized that the leading edge radius does not blend smoothly as required. The reason for the leading edge problem is understood and can be corrected readily (see Section 3.7).

The third set of dimensional analyses were the positions of the forging dies in the isothermal roll forging machine. As explained elsewhere, the dies were cut by EDM to a radius equal to that of the initial roll forging circle of rotation. Sinking of the die to a greater depth without change of radius made it impossible to set the die correctly. Therefore, the observed $t_{max}$ values have been compared both with the drawing requirements as well as the actual die separation.

Table 7 gives the initial values of $t_{max}$ for as-roll forged blades determined in the forge shop with ball point micrometers. The mean and standard deviation are given for the ten blades evaluated. The standard deviations range from 0.0036 to 0.0047 inch about the mean. This compares quite favorably with the drawing tolerance for $t_{max}$ of $\pm$0.0040 inch. When compared with the drawing requirements, the differences for stations N through C, respectively are: +0.0016; +0.0014; +0.0045; +0.0091; +0.0145 and +0.0141 inch. However, when compared with the die gap setting, the differences are -0.0014; -0.0056; -0.0055; -0.0039; -0.0005; and -0.0029 inch. The conclusion is reached that with a corrected die setting, the process as presently established, could produce blades within one standard deviation




| TOL. | ±0°30' | +.005 −.025 | ±.004 | LER | TER | +.004 −.001 | ±.004 | REF |
|---|---|---|---|---|---|---|---|---|
| SECT. | T | K | V | M | J | R | U | N |
| A-A REF | 37°27' | .9569 | .0363 | .0037 | .0035 | .0106 | .0101 | 55°37' |
| C-C | 35°24' | .9530 | .0397 | .0040 | .0039 | .0117 | .0112 | 53°34' |
| E-E | 31°24' | .9526 | .0472 | .0046 | .0047 | .0141 | .0131 | 49°34' |
| G G | 25°45' | .9479 | .0569 | .0053 | .0057 | .0178 | .0152 | 43°53' |
| J-J | 18°57' | .9444 | .0674 | .0059 | .0068 | .0211 | .0175 | 37°07' |
| L-L | 10°58' | .9406 | .0792 | .0066 | .0081 | .0264 | .0200 | 29°08' |
| N-N | 3°11' | .9322 | .0894 | .0071 | .0092 | .0304 | .0220 | 21°21' |
| P-P REF | -0°49' | .9267 | .0931 | .0075 | .0095 | .0319 | .0226 | 17°21' |

Figure 64. Portion of Avco-Lycoming Drawing 2-101-322-03 of T55 Second Stage Compressor Blade

A.

B. Leading Edge

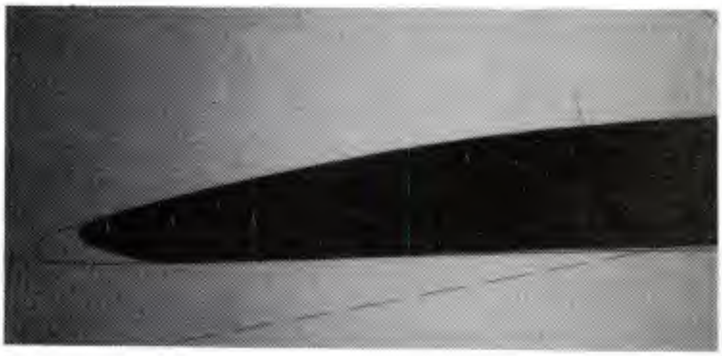
C. Trailing Edge

C. Trailing Edge

Station L-L

Figure 65. Blade Contour Projection On Master Profile: Blade 8-22-1 (Sheet 1 of 2)

D.



E. Leading Edge

F. Trailing Edge

Station J-J

Figure 65. Blade Contour Projection On Master Profile: Blade 8-22-1 (Sheet 2 of 2)

Table 7

Forge Shop Measurements of $t_{max}$
(All measurements $10^{-4}$ inch units)

| Blade | Station | | | | | |
|---|---|---|---|---|---|---|
| | N | L | J | G | E | C |
| 8-22-1 | 920 | 800 | 710 | 630 | 600 | 510 |
| 8-22-2 | 930 | 840 | 760 | 710 | 680 | 610 |
| 8-22-3 | 910 | 830 | 730 | 660 | 610 | 520 |
| 8-23-1 | 1030 | 880 | 760 | 710 | 660 | 570 |
| 8-23-2 | 880 | 750 | 660 | 610 | 580 | 510 |
| 8-23-3 | 860 | 770 | 700 | 640 | 590 | 500 |
| 8-23-4 | 920 | 840 | 760 | 730 | 670 | 570 |
| 8-23-5 | 880 | 770 | 710 | 650 | 610 | 560 |
| 8-23-6 | 870 | 760 | 670 | 600 | 550 | 480 |
| 8-23-7 | 900 | 820 | 730 | 660 | 620 | 550 |
| Mean | 910 | 806 | 719 | 660 | 617 | 538 |
| Standard Deviation | 47 | 43 | 36 | 44 | 42 | 40 |
| Die Gap | 924 | 862 | 774 | 699 | 622 | 567 |
| Drawing | 894 | 792 | 674 | 569 | 472 | 397 |
| Drawing Tolerance (±) | 40 | 40 | 40 | 40 | 40 | 40 |

tolerance band better than 0.005 inch of drawing dimensions. This is approximately where we had expected to be at this stage in the development of the isothermal roll forging process where a target of 0.010 inch of drawing tolerances had been set as a goal.

Comparison of the Gage Room measurements in Table 8 with the Forge Shop values in Table 7 shows very little change in individual measurements. Also, the mean values of $t_{max}$ are essentially the same although three blades had been removed for shipment to Avco. For this reason, the analysis has not been continued at this point.

### 3.9.3 Cost Analysis

Cost analysis is a difficult function because of differences in rates, accounting procedures and available capital equipment between plants. The

Table 8

Gage Room Measurements of $t_{max}$

(All measurements $10^{-4}$ inch units)

| Blade | Station | | | | | |
|---|---|---|---|---|---|---|
| | N | L | J | G | E | C |
| 8-22-1 | 902 | 791 | 693 | 630 | 591 | 508 |
| 8-22-2 | 925 | 839 | 752 | 705 | 677 | 598 |
| 8-23-1 | 1039 | 890 | 764 | 701 | 661 | 583 |
| 8-23-2 | 890 | 780 | 669 | 622 | 591 | 520 |
| 8-23-3 | 858 | 776 | 705 | 638 | 587 | 500 |
| 8-23-4 | 921 | 831 | 760 | 740 | 681 | 571 |
| 8-23-5 | 890 | 783 | 717 | 665 | 626 | 555 |
| Mean: | 918 | 823 | 723 | 672 | 631 | 548 |

approach taken here follows the arguments presented earlier in which the reduced number of operations and reduced amount of handwork were identified as the principal factors.

Table 9 compares the number of operations in the conventional cold roll forging and the isothermal roll forging processes. The principal difference in the processes is the number of roll forging cycles required in the cold process. In comparison, the isothermal roll forging requires a root upset plus rough airfoil roll as the first operation, followed by a finish airfoil roll as the second shaping operation. The additional operation, No. 3, harden and temper in the isothermal process is required to raise the yield stress to prevent buckling in the root upset step. This operation is not required with many materials (e.g., Ti6Al4V) and is necessary with AM-350 only.

Table 9 shows also the unit times for the isothermal roll forging. It is assumed that good industrial practice is used to set up the current technology process for the standard operations, and that the process established at the end of Phase I is used for time estimates on the isothermal roll forging. The estimate is extended to 10,000 blades and includes the following assumptions:

1. No learning on standard operations.
2. The increase discussed in Sections 3.6 and 3.7 for an increase in rolling speed from 1.2 to 3 inch per minute is achieved after 10,000 blades.

## Table 9

Estimate of Manufacturing Costs for AM-350 Compressor Blades
(Size: 1 In. Chord x 3.8 In. Length - Quantity: 10,000 Blades)

| Conventional Cold Rolling | | Isothermal Blade Rolling | | | |
|---|---|---|---|---|---|
| | | | | Unit Time (Min) | |
| Steps | Operations | Steps | Operations | Current Technology | After 10,000 Blades |
| 1 | Cut Strip to Length | 1 | Cut Strip to Length | 0.08 | 0.08 |
| 2 | Precision Grind Thickness | 2 | Degrease | 0.04 | 0.04 |
| 3 | Degrease | 3 | Harden and Temper | 0.10 | 0.10 |
| 4, 8, 12, 16, 21, 25, 30 | Anneal | 4 | Tumble | 0.04 | 0.04 |
| 5, 9, 13, 17, 22, 26, 31 | Lubricate | 5 | Lubricate | 0.08 | 0.08 |
| 6, 10, 14, 18, 23, 27, 32 | Airfoil Roll at 350°F | 6 | Root Upset & Airfoil Roll | 4.2 | 2.4 |
| -, -, -, 19, -, 28, 33 | Rough Trim Length | 7 | Rough Trim Chord | 0.30 | 0.30 |
| 7, 11, 15, 20, 24, 29, 34 | Tumble | 8 | Tumble | 0.04 | 0.04 |
| 35 | Anneal | 9 | Lubricate | 0.08 | 0.08 |
| 36 | Upset Root at 350°F | 10 | Root Press Forge & Airfoil Roll | 4.2 | 2.0 |
| | | 11 | Rough Trim Length | 0.20 | 0.20 |
| | | | | 9.36 | 5.36 |

Common Finishing Operations

Both assumptions are conservative; it is expected, for example, that assumption 2 will begin to be approached at the end of Phase II. Hence, the time estimate at the 10,000th blade represents a reasonable projection. The time of 5 minutes per blade before the common operations of twisting, heat treatment, finishing, etc., will represent savings over the current process.

Although analysis at this early stage strongly supports the earlier analyses showing major cost savings, it is recommended that further effort to refine these figures be delayed until more work has been completed in Phase II. However, the savings for Ti6Al4V blades were known to be greater than for AM-350 and steel blades; this conclusion has been confirmed by the work-to-date on this program.

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